Renewable and Sustainable Energy Reviews 21 (2013) 633–658

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Performance and emission characteristics of biodiesel from different origins: A review

Niraj Kumar [a,*], Varun [b], Sant Ram Chauhan [b]

[a] Department of Mechanical Engineering, Moradabad Institute of Technology, Moradabad-244001 (UP), India
[b] Department of Mechanical Engineering, National Institute of Technology, Hamirpur-177005 (HP), India

ARTICLE INFO

Article history:
Received 19 November 2012
Received in revised form
4 January 2013
Accepted 4 January 2013
Available online 14 February 2013

Keywords:
Biodiesel
Performance
Emission
Fatty acids

ABSTRACT

Alarming situation of world energy stimulated the researchers to look for new sources of fuel, which must be renewable, locally available and environmentally benign. In this regard, the significance of biodiesel as technically and commercially viable alternative to fossil-diesel has led to intense research in the field. Biodiesel is made from different feedstock depending on the availability. This paper analyzes the performance and emission of biodiesel from different feedstock. The main advantage of biodiesel is that it potentially reduces the key pollutants, carbon monoxide, unburnt hydrocarbons and particulate matters. While several researchers have looked at the impact of biodiesel on these pollutants, only few publications discussed the effect of fatty acid composition on performance and emission characteristics. An attempt has been carried out to discuss the effect of biodiesel in terms of performance and emissions based upon composition and properties of the respective biodiesel. The results of the study show that different chemical compositions of biodiesel based upon their origin lead to variation in their properties and performance and emission characteristics. Biodiesel produced from saturated feedstock reduce NO_x emission and resistive to oxidation but exhibit poor atomization. However, many further research needs to be carried out to understand the relationship between the type of biodiesel feedstock and performance and emission.

Contents

* Corresponding author. Tel.: +91 591 2452412; fax: +91 591 2452207.
E-mail addresses: kniraj@yahoo.com, kniraj2006@gmail.com (N. Kumar).

1364-0321/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.rser.2013.01.006

1. Introduction

With the socio-economic growth of the society, the energy requirement has increased multifold globally as the consumption pattern in a particular country depends upon the availability of energy resources. The various sectors that require energy from some sources are industry, transport, agriculture, domestic etc. Different energy sources are wood, coal, petroleum products, nuclear power, solar, wind etc. [1–3]. Out of these, the world surface transport depends primarily on petroleum fuels. The overbearing dependence on petroleum products and related economic and environmental problems have created disquieting situation [4]. The known petroleum reserves are not only limited but also concentrated in certain regions of the world. Furthermore, petroleum reserves are depleting at breakneck pace. The critical situation has stimulated scientists and industries to search for and evaluate alternative fuels for petrol and diesel engines.

The diesel engine is frequently used in transportation, power generation and many miscellaneous applications including industrial and agricultural. The major pollutants from diesel engine are smoke, particulate matter (PM), carbon monoxide (CO), Nitrogen oxides (NO_x) and unburnt hydrocarbon (UBHC). Among different pollutants, the most significant are smoke and nitrogen oxides [5–9]. For achieving this goal, two methods have been followed; adaptation of the engine to the fuel and adaptation of the fuel to the engine. Considering the large numbers of existing engines, the second strategy seems to be more apropos [10,11]. Hence, there is a need to explore a viable alternate fuel that can be used in compression ignition (CI) engines. Any such alternative should not only match the performance of diesel but also meet or exceed the current emission norms. Harvesting renewable energy has also become an important energy source worldwide [12–14]. The alternate fuel must be readily available, technically feasible, economically viable and also meet the pollution norms.

One of the possible alternatives to the fossil fuel is vegetable oil. The development of vegetable oil started about a century ago. Also during World War II, vegetable oils were used as fuel in emergency situations [15,16]. In principle, any vegetable or seed oil which essentially comprises triglycerides of long chain saturated and unsaturated fatty acid can be used in diesel engines. This fuel is biodegradable, non-toxic and above all, has emission profile comparable to diesel [17,18]. The characteristics of vegetable oils fall within a fairly narrow band and are quite close to those of diesel. However, the initial research to use vegetable oil as a fuel for diesel engine resulted in some negative impact on engine. It has been shown in previous work [19,20] that utilization of vegetable oils in diesel engine leads to problem in pumping, atomization, gumming, injector fouling, piston ring sticking and contamination of lubricating oil in the long run operation. It is due to high viscosity, density, iodine value and poor non-volatility. Hence, it is essential to reduce the viscosity for better combustion of the vegetable oils by using methods such as preheating, thermal cracking and transesterification. Transesterification is primarily used to convert vegetable oil to a form that can be used in diesel engines [21–23] and is called biodiesel. Biodiesel can be defined as mono-alkyl esters of long chain fatty acids derived from vegetable oils or animal fats which conform to the ASTM (American Society for Testing and Materials) specification for use in diesel engine [24]. It is considered a clean fuel as it has almost no sulfur, no aromatics and has about 10% built-in oxygen, which helps it to burn completely and also gives it a high cetane number. Biodiesel may be easier to commercialize than other alternative fuels, and hence numerous vegetable oils have been tested as biodiesel [25]. Kalayasiri et al. [26] surveyed 364 different plant seed oils as promising fuel for diesel engine, both in the pure oil form as well as in the form of fatty acid methyl esters,. In general, biodiesel feedstock can be divided into four categories [27–32]:

(1) Edible vegetable oil: Sunflower, Rapeseed, Rice bran, Soybean, Coconut, Corn, Palm, Olive, Pistachia Palestine, Sesame seed, Peanut, Opium Poppy, Safflower oil etc.
(2) Non-edible vegetable oil: Jatropha, Karanjaor Pongamia, Neem, Jojoba, Cottonseed, Linseed, Mahua, Deccan hemp, Kusum, Orange, Rubberseed, Sea Mango, Algae and Halophytes etc.
(3) Waste or recycled oil.
(4) Animal fats: Tallow, yellow grease, chicken fat and by-products from fish oil etc.

The production and utilization of biodiesel as diesel fuel has been well tested and evaluated in several countries. Also, due to its properties similar to those of diesel, it can be used as a viable substitute without any significant modification in existing diesel engine, as well as fuel storage and distribution infrastructure [33]. The goal of the present study is to evaluate the performance and emission of the diesel engine operating on biodiesel in relation to the effects of fatty acid composition and types of feedstock.

2. Current scenario of biodiesel

2.1. Global scenario

Due to energy crisis of the 1970s, many countries developed different renewable energy technologies in order to reduce dependence on import of fossil fuels, while many others have pursued renewable energy development to protect the environment. Energy cost depends upon certain factors such as natural resource endowments, political and economic systems, and cultural tradition of countries. The importance of biodiesel can be well visualized by the

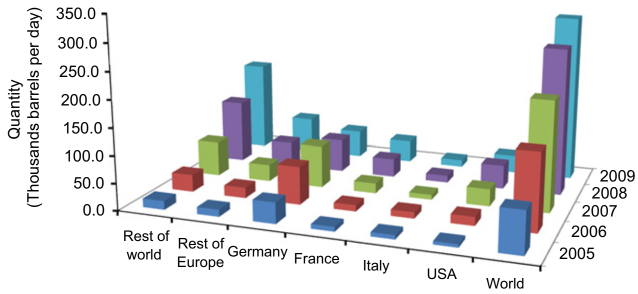


Fig. 1. Production of biodiesel in world.

fact that fossil-based oil, coal and gas reserves will be exhausted in less than another 10 decades [34]. The estimated production of vegetable oil feed stock worldwide is estimated to be 100 million tonnes [35]. The production of biodiesel has registered commendable increase during the past ten years. The consistent development in the production of biodiesel is shown in Fig. 1 [36].

The biodiesel production in the European Union (EU) has increased from 1065 thousand tonnes in 2002 to 10289 thousand tonnes in 2007 due to the initiative of the European Commission (EC) to promote biodiesel [37]. Two draft directives by the council of Europe and the European parliament, concerning the reduction of the GHG (Greenhouse Gases) emissions and energy supply diversification, have contributed a lot towards the development of biodiesel [38]. In the EU, rapeseed oil, sunflower oil and cottonseed oil are the preferred feedstock [39–41]. In UK, most of the biodiesel is being produced from waste vegetable oil (WVO) which is the cheapest feedstock [42]. UK produced 9000 t of biodiesel in 2004 [43]. Among EU countries, France has been very consistent in implementing policies related to biofuels since last 20 years. Biofuel was one of the key points of the climate plan introduced by the French Government. However, Germany has taken lead in the production of vegetable oil methyl ester (VOME) in the year 2001 with a production of 2,662 thousand tonnes, followed by France (743 thousand tonnes), whereas Italy (447 thousand tonnes) and UK (192 thousand tonnes) rank 3rd and 4th, respectively [44]. Spain exempted biodiesel from fuel excise tax to promote the consumption of biodiesel on 1st January, 2000 [45]. The Greek Government also started its biodiesel program following European Directive on the promotion of the use of biofuels for transport [41]. Biodiesel in Lithuania is produced from rapeseed [46].

In the USA, there are more than 170 biodiesel plants with soybean as the main feedstock for production of biodiesel [47]. A blend of 20% biodiesel with 80% diesel (B20) is considered to be the most suitable for transportation sector [48,49]. In Energy Policy Act 1992 of the USA, biodiesel has been recognized as alternative fuel for vehicles. Environmental Protection Agency (EPA) also recognizes biodiesel because of its less harmful effect on human health [50]. The Brazilian biodiesel program was created by the Ministry of Science and Technology in October 30, 2002 [51]. Soybean, sunflower, peanut, cotton, castor bean, rapeseed, palm and coconut are the main oil seeds in Brazil and the government authorized addition of biodiesel (5%) to diesel [52]. Brazil has 47 biodiesel plants authorized to operate [53]. The municipal government and non-governmental organizations (NGOs) in Japan are utilizing mainly recycled rapeseed oil as the main feedstock for producing biodiesel. As of March 2008, the total amount of biodiesel production was estimated at 10,000 kiloliter. Japan has started around twenty biodiesel fuel projects since 2007 [54]. Pakistan has identified *Pongamia pinnata*, rapeseed and castor bean as potential resource for production of biodiesel. The Alternative Energy Development Board is planning for a pilot plant, while biodiesel based power generation power plant is to be installed in one village under National Rural Electrification Program [1]. Taiwan biodiesel program started in 1998 and the Energy and Environment Research Laboratory [EERL] has experimented with soybean biodiesel and established a pilot plant of capacity 3000 metric tonnes using soybean [12]. In Tanzania, current initial activities have been directed towards the use of *Jatropha curcas* Linnaeus, an indigenous plant, to explore the potential of bio-fuels [55].

2.2. Indian scenario

The growth of Indian economy in 2009–2010 was estimated as 8.0% by quick estimate released on 31 January 2011 and 8.6% in 2010–2011 as per the advance estimates of Central Statistics Office (CSO) released on 7 February 2011[56]. Despite a slowing global economy, India stood as fourth largest energy consumer in the world, after the US, China and Russia, in the year 2009. The combination of rising oil consumption and relatively flat production (Fig. 2) has left India increasingly dependent on imports to meet its petroleum demand [57]. India is one of the top 10 oil consuming countries in the world. The country's existing annual crude oil production is at about 32 million tonnes as against the demand of about 110 million tonnes [58]. In India, bulk of the freight (over 60%) and passenger traffic (over 80%) is carried by road; and diesel and petrol contribute to 98% of the energy consumed in the transport sector [59]. Oil imports during April–May 2007 were valued at US$ 9165.20 million and the oil import bill is expected to rise to $120 billion in 2011–2012 [60].

To reduce the dependency on imported oil, production and utilisation of biodiesel may be a solution in a developing country like India. In India, the demand of edible oil is much higher than its domestic production thus the edible oil cannot be diverted for the production of biodiesel. This fact is well established by the production and import data of edible oil (Fig. 3) [61]. Being a tropical country, India has high forest land having a large range of trees which yield significant quantity of oil seeds. The main non-edible oils in India are Neem (*Azadirachta indica*), Mahua (*Madhuca indica*), Karanja (*P. pinnata*), Sal (*Shorea robusta*), Kusum (*Schleichera oleosa*) and Ratanjyot (*Jatropha curcus*) and their productions are about 100,000, 180,000, 55,000, 180,000, 25,000 and 15,000 t per annum, respectively [62]. The possibility of commercial production of Jatropha, Karanja and Mahua has been explored for biodiesel. These crops not only can meet the oil demand for biofuel production but can also green the wastelands in drought prone areas without sacrificing the food and fodder security and to improve the livelihoods of the rural poor.

The biodiesel programme of the Government of India has been proposed in two phases. The first phase is demonstration phase which consists of plantation in 0.4 million hectares land covering

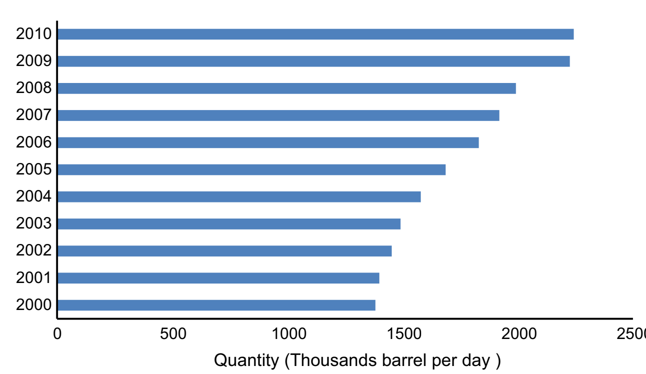


Fig. 2. Difference between production and consumption of oil in India.

26 states. While the second phase will consists of self-sustaining production of biodiesel which will help in achieving the 20% blending of biodiesel [63]. Public sector oil companies in India have offered an assured buy back price for biodiesel at Rs. 25 per liter. The MoRD (Ministry of Rural Development) has prepared a DPR (detailed project report) on the National Mission on biodiesel. MoRD has also identified various end uses for non-edible straight vegetable oil (SVO), like, transport application and power generation on a decentralize basis apart from conversion of SVO to biodiesel [64,65].

Azam et al. [66] have studied the profile of 75 indigenous plant species of India. Among these 26 plant species were found to be most suitable for use as biodiesel on the basis of biodiesel standards of US (ASTM D 6751-02, ASTM PS 121-99), Germany (DIN V 51606) and European Standard Organization (EN 14214). A comprehensive program on biofuel has been started by MNRE (Ministry of New and Renewable Energy) in 2002–2003. Pilot demonstration program in rural area has also been started by the MNRE [67]. Though, Indian biodiesel program is still in nascent phase, it has enormous potential. At this stage, it is beneficial for India to restructure its research and development program in order to deal with the different related issues like utilisation of biodiesel and its impact on different section of society, improving the productivity of plant and oil extraction technique.

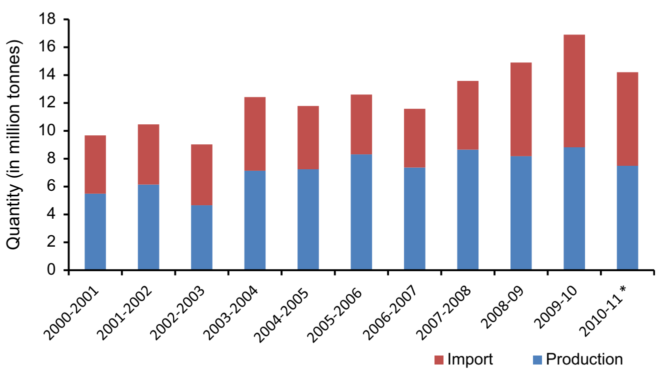


Fig. 3. Production and Import of edible oil in India.

2.3. Economics of feedstock

The global scenario of biodiesel is promising. One of the reasons hindering the widespread application of biodiesel is the cost of the biodiesel. Generally consumers opt for cheaper product than the green. The cost of biodiesel is higher than diesel fuel. In the US the biodiesel sells for about US$0. 396 to US$0. 528 per liter before taxes. The rough projections of the cost of biodiesel from vegetable oil and waste grease are, respectively, US$0.54–0.62/l and US$0.34–0.42/l. At the same time the pre-tax diesel priced is US$0.18/l in the US and US$0.20–0.24/l in some European countries [68]. The cost of biodiesel in different countries is shown in Table 1.

There is no single cost for biodiesel production, but rather a wide range of costs prevailing in different countries depending upon a number of factors. The cost of the biodiesel project could be broken into raw material cost, capital cost and operating cost. Raw materials contribute to a major portion of the cost of biodiesel production more so than the size of the industrial plant [73]. In fact, the average cost of raw material for biodiesel production is nearly 60 to 75% of the total production cost. The overall cost of the biodiesel is also affected by the season of the year, low quality, inconsistent in the product quality and poor product yield etc. [25]. Further, the price of biodiesel depends on factors such as fuel preparation, transportation, consumption and requirement in the country [46]. However, reductions in cost of biodiesel can achieve through scale economies and learning effects. In addition more investment is required in technologies and systems for second generation biofuels [42].

Table 1
Estimated cost and primary feedstock of biodiesel in different countries.

Ref.	Country	Primary feedstock	Cost ($/L)	Remarks
[34,70]	Malaysia	Palm oil, jatropha	0.53	For all available lipid feedstock prices
[34,70]	Indonesia	Palm oil wastes, jatropha	0.49	–do–
[34,70]	Argentina	Soybean	0.62	–do–
[34,70]	USA	Soybean	0.70	–do–
[34,70]	Brazil	Soybean, Palm, sunflower and castor	0.62	–do–
[34,70]	Netherlands	Soybean	0.75	–do–
[34,42]	Germany	Rapeseed, animal fat	0.79	–do–
[34,42,70]	Philippines	Coconut oil	0.53	–do–
[34,42]	Belgium	Rapeseed, animal fat	0.78	–do–
[34,71]	Spain	Rapeseed	1.71	–do–
[34,72]	India	Jatropha, karanja	0.63–0.72	
[13]	Latvia	Rapeseed, Sunflower	0.56	Prevailing figures (2007)
[13]	Lithuania	Rapeseed, Sunflower	0.54	Prevailing figures (2007)
[13]	Hungary	Rapeseed, Sunflower	0.86	Prevailing figures (2007)
[13]	Poland	Rapeseed, Sunflower	0.99	Cost in 2002
[13]	Slovakia	Rapeseed, Sunflower	0.93	Cost in 2002
[13]	European Union	Rapeseed, sunflower	0.30–0.69	Oilseed or animal fats
			0.54–0.62	Vegetable oil
			0.34–0.42	Waste grease
[69]	Thailand	palm and coconut oil, waste cooking oil and animal fat	0.84	Cost in 2008
[41]	Greece	Sunflower, rapeseed	0.77–1.08	For sunflower
[41]			1.38	For rapeseed
[41]			0.90–1.32	For cotton seed
[12]	Taiwan	WVO, sunflower, soybean	0.90	WVO
			1.92	Sunflower
			1.59	Soybean
[42]	UK	WVO	0.46[3]	WVO
			0.81[3]	Palm oil
			0.88[3]	Rapeseed

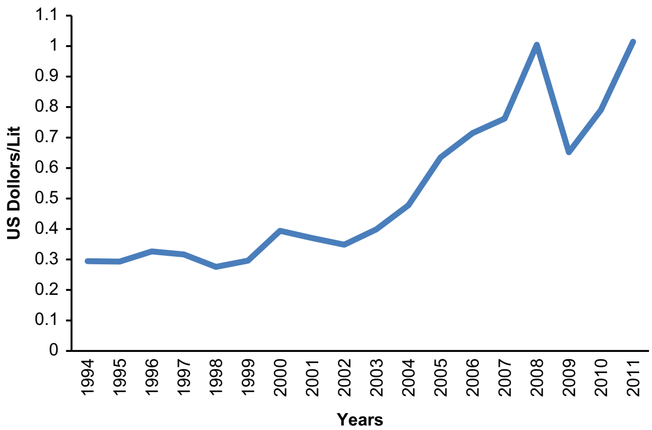


Fig. 4. Cost of US No 2 diesel retail price [57].

Compare to the diesel price in the US (Fig. 4), biodiesel is thus currently not economically feasible, and more research and technological development will be needed to make biodiesel more competitive in terms of cost [68,74] In addition, for biofuels to become commercially successful on a large scale will require favorable economics at each point along the supply chain of biodiesel industry, namely, Feedstock production, Feedstock logistics, Biodiesel production, Biodiesel distribution, Biodiesel end use [47].

3. Performance and emissions of biodiesel from different origins

The performance parameters such as power output, specific fuel consumption, brake thermal efficiency along with tail pipe emissions like Carbon monoxide (CO), Hydrocarbon (HC), Nitrogen oxides (NO_x), Particulate matter (PM), smoke of different biodiesels had been reviewed. In general, biodiesels are characterized by their heating value, cetane number, viscosity, density, cold flow properties such as cloud and pour points, flash point, ash content, sulfur content, carbon residue, and acid value. These physical and chemical properties of biodiesel depend on the characteristics of feedstock such as carbon chain length, saturation, location and types of double bond (*cis* or *trans*) etc. It has been demonstrated that engine performance and exhaust emissions depend on these physical and chemical properties; for this reason, it may be inferred that engine performance and emissions must be correlated to the feedstock of biodiesel.

3.1. Non-edible oils

3.1.1. Jatropha curcus

J. curcus is a draught resistance shrub or tree, mainly cultivated in Central and South America, South East Asia, India and Africa [75]. It belongs to the Euphorbiaceae family consisting of around 800 species [76]. It can thrive in a number of climatic zones with a plant life of about 50 years [77]. Yield depends on a range of factors such as water, soil conditions, altitude, sunlight and temperature [55]. The oil content of jatropha seed ranges from 30 to 40% by weight and the kernel itself ranges from 45 to 60% [78]. The presence of some toxic components renders this oil unsuitable for use in cooking [79] and makes its use for fuel production very attractive.

Agarwal and Agarwal [80] conducted experiments on a single cylinder, 4-stroke, constant speed, water cooled, direct injection diesel engine employing preheated jatropha oil (using waste heat of the exhaust gases) and various blends of jatropha oil with diesel. Heating jatropha oil up to 100 °C brings down the viscosity in close range to diesel. Based on experimental data related to (brake specific fuel consumption) BSFC, brake thermal efficiency (BTE), smoke opacity, and optimum fuel injection pressure (200 bar) were found same for both the fuels. BTE for preheated jatropha oil was lower than diesel but higher than unheated jatropha oil. Also, BTE for blends was found lower than diesel. Lower blend concentrations and preheated jatropha oil showed promising results in terms of performance and emissions. Forson et al. [81] performed tests on a single-cylinder direct injection engine operating on diesel fuel, jatropha oil and blends of diesel and jatropha oil in proportions of 97.4/2.6,80/20, and 50/50% by volume. For tested fuels, increase in BTE, brake power (BP) and reduction of specific fuel consumption (SFC) were found, while emission of CO_2 was similar and the emission of CO was higher as compared to diesel. The authors suggested that jatropha oil can be used as an ignition accelerator additive for diesel fuel. In another experiment performed on a single cylinder, constant speed, direct injection diesel engine with neat jatropha oil as fuel, Reddy and Ramesh [82] demonstrated that for successfully utilizing neat jatropha oil in diesel engines, different parameters such as swirl, injector opening pressure, injection rate and injection timing have to be optimized. Though the thermal efficiency of the modified engine with jatropha oil (28.9%) was lower than diesel (32.1%), the other parameters such as HC, NO and smoke emission were reported to be lower than diesel by 33.3, 33.9 and 25.9%, respectively, at full load. While experimenting with neat jatropha biodiesel and different blends, the results show that BTE of jatropha methyl ester and its blends with diesel was lower than diesel, while BSFC and brake specific energy consumption were found to be higher. The emission parameters such as HC, CO and smoke were found to be lower with jatropha biodiesel fuel. In contrast NO_x and CO_2 emissions increased with jatropha biodiesel and its blends. Maximum cylinder gas pressure and heat release were found to be lower for biodiesel and its blends [83]. Rao et al. [84] conducted tests on a single cylinder, 4-stroke, naturally aspirated, air cooled diesel engine coupled with an electrical dynamometer and shown that ignition delay, maximum heat release rate and combustion duration were lower for JME (jatropha methyl ester) and its blends compared to diesel. Except NO_x, other exhaust emissions were reduced with the application of biodiesel compare to diesel.

Jindal et al. [85] evaluated the effects of engine parameters (compression ratio and injection pressure) while working with jatropha methyl ester as fuel in single cylinder, water cooled, 4-stroke, VCR (variable compression ratio) diesel engine connected to eddy current type dynamometer. The results show that increase in compression ratio associated with increase in injection pressure improve the performance of the engine. With regard to emission aspects, for all combinations of compression ratio and injection pressure, the emissions of HC, NO_x, smoke opacity and exhaust temperature were lower with biodiesel against that of diesel fuel. Finally, the optimum combination was found as compression ratio of 18 with injection pressure of 250 bar.

3.1.2. Pongamia pinnata/karanja

The growth of karanja tree is fast and it can reach up to a height of 40 ft. Karanja belongs to humid and subtropical environments; however, it can thrive in areas having an annual rainfall ranging from 500 to 2500 mm. The seed oil has a high content of triglycerides. Mahanta et al. [86] utilised pure karanja oil and its blends along with biodiesel of karanja and tested in a 5-HP water cooled, direct injection, four stroke diesel engine. The SFC of B15 and B20 blends were marginally higher than diesel. The SFC increased with increase in straight vegetable oil (SVO) content in

the blend, though with B15 and B20, fuel consumption decreased marginally when compared with SVO blends. In comparison to diesel, the blends of methyl ester of karanja oil and diesel particularly B15 and B20 gave higher brake thermal efficiency. However, SVO blends resulted in lower thermal efficiency as compared to diesel. Also, emissions of CO and HC were reduced with B15 and B20 especially at medium and higher load. Agarwal and Rajamanoharan [15] have conducted experiment to investigate the performance and emission characteristics of a CI engine fuelled with karanja oil and its blends (10, 20, 50 and 75%) besides diesel with and without preheating/pre-conditioning. Considerable improvements in terms of performance and emission have been reported with lower blends of karanja oil, either preheated or unheated. With preheated oil blends, maximum thermal efficiency of the engine was found nearly 30% and for lower blends (up to 50%) and unheated, it was 24–27%. The emitted smoke from preheated lower blends as well as unheated lower blends was almost similar to that of diesel fuel, while for the same blends HC emission was lower. The emission of NO_x from all blends with and without preheating was lower than diesel at all load conditions.

Sureshkumar et al. [87] have conducted experiments on single cylinder 4-stroke, water cooled and constant speed CI engine with varying blends of *P. pinnata* methyl ester (PPME) and diesel. For the blends B20 and B40, the BSFC is lower than and equal to that of diesel, respectively. However, further increase in PPME concentration in the blend resulted in increase in the BSFC at all loads and the BSEC (brake specific energy consumption) was less than that of diesel at all loads. The engine emitted more CO for diesel as compared to PPME blends under all loading conditions. The lower percentage of PPME blends emitted less amount CO_2 in comparison with diesel; while with higher content of PPME in the blend, an increase in CO_2 emission was noted. For all blends and for all loading conditions the emission of HC was negligible and emission of NO_x was lower as compared to diesel. In a performance test conducted on twin cylinder vertical high speed diesel engine using karanja methyl ester and blends, Srivastava and Verma [88] have shown that methyl ester of karanja oil have slightly reduced thermal efficiency as compared to diesel. The maximum thermal efficiency reported for methyl ester of karanja oil was about 24.87% compared to 30.59% for diesel. An increase in the exhaust gas temperature (EGT) and slight increases in BSFC were reported for methyl ester compared to diesel and blends. At peak load, the difference in EGT was around 12%. In comparison to diesel, methyl ester of karanja oil emitted higher emission of HC, CO and NO_x with maximum difference of 41, 17 and 12%, respectively. The CO emission with lower concentration of biodiesel (up to B20) was found similar to diesel. Performance and exhaust emission characteristics of the engine were determined using diesel as the baseline fuel and different blends of diesel and biodiesel (methyl and ethyl esters of karanja oil) as test fuels [89]. It is evident from the results that methyl esters produced slightly higher power than ethyl esters. Decrease in thermal efficiency and increase in fuel consumption were reported with utilisation of biodiesel. Among the blends, methyl esters show better performance and emission characteristics. Exhaust pollutants from CI engine – typically CO, HC and smoke – were reduced with the use of neat biodiesel and the blends. At part load, NO_x emissions increased by 10–25% when fuelled with biodiesel and its blends compare to diesel. However, at full load diesel emitted more NO_x than esters.

3.1.3. Cottonseed oil

Karabektas et al. [90] investigated performance parameters and exhaust emissions test with preheated COME (Cotton oil methyl ester) at different temperatures, namely 30, 60, 90 and 120 °C. The test results revealed that preheating COME up to 90 °C had favourable impacts on the BTE and CO emissions but caused higher NO_x emissions as compared to diesel. Additionally, slight increase in the BP was reported with the preheating temperature up to 90 °C, still the BP was less than diesel. Preheating COME beyond 90 °C shows a negative effect on BP.

Nabi et al. [91] conducted the experiment on a single cylinder, water-cooled, 4-stroke, DI diesel engine with diesel and blends of cottonseed biodiesel up to 30%. The authors have affirmed the reduction in carbon monoxide (CO), particulate matter (PM) and smoke. The maximum reduction for CO was 24% for B30, while in the case of PM it was 24% for B20 and finally for smoke the maximum reduction was 14% for B10. However, a slight increase in oxides of nitrogen (NO_x) emission was experienced for different biodiesel mixtures. The maximum increase of 10% was found with B30. BTE of all biodiesel mixtures was determined to be slightly lower than those of diesel. As expected, BSFC values were reported higher than diesel fuel. The test performed on cottonseed oil biodiesel and its blends in a single cylinder, 4-strokes, air-cooled diesel engine with different mixture of CSOME (Cotton seed oil methyl ester) in diesel, ranging from B5 to B100, revealed the influences of blends on performance and emissions. The results show a decrease in power and an increase in BSFC for B100. But no significant change in performance was reported for lower concentration of biodiesel up to B20. Also, the lowest EGT was recorded for B20 with a value of 395 °C in comparison to 469 °C for diesel. A decrease in emissions of CO, SO_2 and NO_x were reported for all blends of biodiesel. The smoke emissions were reported to be reduced for medium blends (up to B50) and then increases for higher blends (B75, B100)[92]. While, He and Bao [93] adopted a quadratic regressive orthogonal design test method to examine the relationship between specific fuel consumption and four adjustable working parameters namely intake valve-closing angle (a), exhaust-valve-opening angle (b), fuel-delivery angle (q) and injection pressure (P). The author concluded that the fuel-delivery angle was found to be the cardinal factor affecting the specific fuel consumption. The optimum value for fuel-delivery angle, in case of engine fuelled with biodiesel was found approximately 3–5° in advance, in comparison to the diesel-fuelled engine.

3.1.4. Rubberseed oil

The availability of rubber seed is about 30 thousand MT per year in India. Rubber seed kernel constitutes of 50–60% of the seed and about 40–50% of pale yellow oil. The major saturated fatty acids are palmitic (10.2%) and stearic (8.7%) while the main unsaturated fatty acids are oleic (24.6%), linoleic (39.6%) and linolenic (16.3%) [94]. Free fatty acid (FFA) content in unrefined rubber seed oil is about 17% [95].

Ramadhas et al. [96] carried out a series of tests on a constant speed (1500 rpm),4-stroke, direct injection, water cooled, single cylinder, CI engine with blends of rubber seed oil and diesel as fuel. Highest thermal efficiency of the engine was observed with blend having 20% rubber seed oil, while blend with 40% rubber seed oil emitted lowest smoke. SFC for rubber seed oil was higher than that of diesel. Carbon deposits on piston surface and combustion chamber were found to be slightly larger with blend in comparison to that of diesel. Utilization of blends requires frequent cleaning of fuel filter, pump and the combustion chamber. Ramadhas et al. [97] reported 1% lower BTE, 12% more fuel consumption for biodiesel compared to diesel in the test conducted with rubber seed oil, rubber seed oil biodiesel and its blend on a 4-stroke, direct injection, naturally aspirated single cylinder diesel engine. The reduction in CO and smoke density in exhaust gas was

reported to increase with increasing concentration of biodiesel in the blend.

A theoretical model was developed by Ramadhas et al. [98] to analyze the performance characteristics of the CI engine fuelled by biodiesel and its blends. The performance tests are carried out on a CI engine using biodiesel and its blends with diesel (B20 and B100) as fuel. This model predicted the engine performance characteristics in close approximation to that of experimental results. The performance of B20 oil blends was found comparable to diesel.

3.1.5. Linseed oil

Viscosity of linseed oil is around 8 times higher than diesel but that of linseed oil methyl ester (LOME) is almost equal to diesel. After transesterification, flash point of linseed oil decreases but still remains higher than that of diesel and cetane number of LOME is also higher than that of diesel. Agarwal and Das [99] conducted experiment on different blends of LOME and shows that higher and lower concentrations of biodiesel have different effects on performance and emission of engine. Thermal efficiency of the engine improved by increasing the concentration of biodiesel in the blend and after a certain limit of biodiesel concentration, reverse trend was observed and it started decreasing. But in all the cases, all the blends had a higher thermal efficiency than that of diesel fuel. Increasing the concentration of LOME in biodiesel blend increased the exhaust temperature especially at higher load. Smoke opacity was found to be lower with lower concentration of biodiesel. The 20% biodiesel was found to be the optimum concentration. NO_x emissions with biodiesel fuel were higher by approximately 5%. Puhan et al. [100] investigated linseed oil methyl ester in a constant speed DI diesel engine with varied fuel injection pressures (200, 220 and 240 bar). Injection pressure was optimized at a pressure of 240 bar. At optimised pressure, the thermal efficiency improved and was found to be similar to diesel. A reduced emission in carbon monoxide, unburned hydrocarbon and smoke emissions was also observed compared to diesel. However, increase in the NO_x was reported in comparison to diesel.

Agarwal et al. [101] utilised LOME fuel to test the engine, first for its performance and emission characteristics and then to study the effect on various parts of the engine in the long-term endurance test. B20 was found to be best blend on the basis of performance and emission. Also, wear of various vital parts reduced up to 30% and ash content was found to be lower than diesel. Similar results were reported and shown substantially lower wear for biodiesel as compared to diesel and thus improved life for biodiesel operated engines [102].

3.1.6. Mahua oil

Mahua oil (MO) is non-edible oil which is widely available in India and neighbouring countries. The density and viscosity of mahua methyl ester were observed to be about 4 and 53% higher than that of diesel [103].

Agarwal et al. [104] investigated the performance and emission characteristics of linseed oil, mahua oil, rice bran oil and LOME and their blends in a stationary single cylinder, 4-stroke diesel engine and compared it with diesel. The results show that 30% mahua oil blend was not only most thermally efficient but also provided marginally better BSEC than other oil blends. However, smoke density was higher for mahua blends compared to diesel at lower loads. Raheman and Ghadge [103] tested different blends of methyl ester of mahua oil (MOME) in a Ricardo E6 engine, the results enunciate that reduction in exhaust emissions and BSFC together with increased BP, BTE made the blend of biodiesel (B20) a suitable alternative fuel for diesel. An engine testing was conducted on a single-cylinder 4-stroke direct-injection, constant-speed CI diesel engine using MO, MOME and B20 (20% MOME and 80% diesel) as fuels. It had been observed that the B20 blend gave higher efficiency (at higher loads) and MO gave lower thermal efficiency than diesel fuel [105]. MOME gave lower smoke opacity but MO resulted in higher smoke emission among all fuels. 158 HP rated power, turbocharged, DI, water cooled diesel engine was run on diesel, methyl ester of mahua oil and its blends at constant speed of 1500 rpm under variable load conditions [106]. The experiments show that the BSFC increased and BTE decreased with increase in the proportion of biodiesel in the blends. The amount of CO and HC in exhaust emission reduced, whereas amount of NO_x increased with the increase in percentage of mahua biodiesel in the blends. Puhan et al. [107] have tested mahua oil ethyl ester (MOEE) in a four stroke naturally aspirated direct injection diesel engine and reported an increase in BSFC and a slight increase in BTE for MOEE compared to diesel. The emission of carbon monoxide, hydrocarbon, oxides of nitrogen and smoke were decreased by 58, 63, 12 and 70%, respectively. Puhan et al. [108] experimented with methyl ester (MOME), ethyl ester (MOEE) and butyl ester (MOBE) of Mahua oil in a 4-stroke, direct injection diesel engine. Total fuel consumption (TFC) for esters was higher than diesel. For methyl ester thermal efficiency was found to be better compared to other fuels while maximum exhaust temperature was recorded for MOME. In contrast to CO_2 emission, CO and NO_x emissions from all esters were lower than diesel. The authors concluded that the MOME was better fuel than other two esters in terms of performance and emission.

3.1.7. Algae

Algae are essential in the food chains of the entire world. All algae are primarily made up of proteins, carbohydrates, fats, and nucleic acids in varying proportions. There is a growing awareness for the utilisation of algae for production of biodiesel because of its higher yield non-edible oil production and its fast growth. Moreover, its production does not require land, hence poses no conflict with food production. It is reported that around 50% of algae weight is oil and this lipid oil can be converted into biodiesel. In comparison to crops currently employed in biodiesel production, algae yield 30 times more oil per acre [109,110]. Cultivation of algae does not require fertile land, rather it can be cultivated almost anywhere, including sewage or salt water [111].

Haik et al. [112] tested algae oil and its methyl esters in an indirect injection diesel engine to evaluate the effects of engine speed, engine load output, injection timing and engine compression ratio. Among all the fuels tested, algae oil methyl ester exhibited more combustion noise but produced less engine torque output. It was also found that algae oil methyl ester produced slightly higher heat release rate in comparison to diesel.

3.2. Edible oils

3.2.1. Coconut oil

Coconut oil belongs to lauric oil group of vegetable oils. More than 90% of fatty acids of coconut oil are saturated and the iodine value is around 7–12 [113]. Coconut oil has a special property of readily mixing with diesel. At temperature below 20 °C, it remains as a white crystalline solid, but it turns into clear liquid when it is blended with ordinary diesel. Unlike other vegetable oils, coconut oil does not form any layer on the inside wall of the fuel tank when blended with diesel [114].

Raffiq and Ahmed [115] utilised three different methods to improve the combustion characteristics- incorporating a copper perforated medium beneath, using coconut oil directly as an

additive to diesel and finally preheating the coconut oil blended diesel. The analysis shows that preheated (50%) coconut oil blends were found to be better in terms of both emission and performance. Without preheating, 20% coconut oil blends gave optimum results, but SEC and emissions were higher than those of preheated blends.

Performance and emission analysis have been carried out on four-cylinder, indirect diesel engine with coconut oil blends [116]. The engine was operated with varying speed from 800–3200 rpm, while endurance test was performed at 2000 rpm with varying loads. BP of the engine was found comparable to that for pure diesel and blends of coconut oil; however, adding 10–30% coconut oil in the blend produced higher BP than diesel. Blends with 40–50% coconut oil developed low BP due to the slow initial rate of burning. The SFC increased with increasing percentage of coconut oil in the blend. Cylinder pressure and the heat release produced by the blend containing 10–30% coconut oil was found similar to pure diesel, although the calorific value of the coconut oil is 6% less than diesel. Emissions of HC, CO, and smoke reduced with the increasing content of coconut oil in blend. The concentration of NO_x was reduced to 8.42%. However, emission of CO_2increased with increasing coconut oil in the blend. For all fuel blends, no significant carbon deposition was found in the injector nozzle tips. Smooth operation of engine was not affected by initial starting and knocking. Singh et al. [117] tested hybrid fuels consisting of coconut oil, aqueous ethanol and a surfactant (butan-1-ol) as a fuel in a direct injection diesel engine. The results revealed that the engine efficiency of the hybrid fuels was similar to diesel and the SFC of the hybrid fuels was higher in comparison to diesel. The emissions levels (NO, SO_2 and CO_2) of the hybrid fuels were found to be lower than diesel, but an increase in the CO emission was observed.

3.2.2. Soybean oil

Biodiesel from soybean oil is highly unsaturated and highly prone to oxidatione specially at higher temperature [118]. Viscosity, surface tension and specific gravity of the soybean oil methyl ester are relatively higher than diesel [119]. Pour point and cloud point are high which makes fuel unsuitable under cold weather condition. Pryor et al. [120] tested 100% crude soybean oil, crude degummed soybean oil and soybean oil ethyl ester (SOEE) as a fuel in a diesel engine. Power output of the engine running on soybean oil and its ester were almost similar to the engine running on diesel. For the entire load range, BSFC for soybean oil and its ester were 11–13% more than that for diesel. The EGT with soybean oil was 2–5% more than diesel, but with soybean ester the EGT was 2–3% less than that of diesel. There was improvement in combustion characteristics for soybean ethyl ester in comparison to diesel. The presence of oxygen in ester raised the stoichiometric fuel air ratio of the ester fuels [121]. Performance, emissions and combustion characteristics of the single cylinder, naturally aspirated, 4-stroke, water cooled, direct injection, high speed CI diesel engine were analyzed using diesel and biodiesel as fuels [122]. For the entire range of experiments, power output of biodiesel was almost similar to diesel but the BSFC was higher as compared to diesel. However, soybean biodiesel provided positive impact in terms of emission of CO, HC, NO_x and smoke with reduction of 27, 27, 5, and 52%, respectively, under speed characteristic at full engine load. The combustion of soybean biodiesel in the unmodified engine resulted in advanced combustion compared to diesel. Osborne et al. [123] have shown in their experiments, with line-haul locomotive with 3280 kW rated traction power, that biodiesel reduced rated power with 7% increase in fuel consumption. In line-haul cycle, PM reduced by 20%, CO reduced by 24%, NO_x increased by 15% as compared to diesel. For biodiesel, HC was reduced by 21% and 24% over the line-haul and switch cycles, respectively. In a different study Kim et al. [124] tested biodiesel derived from soybean oil in a single cylinder, four stroke engine equipped with a common-rail electric controlled fuel injection system with varying engine speed, EGR, and intake pressure. The results revealed lower hydrocarbon and carbon monoxide emissions and higher NO_x for biodiesel compared to diesel fuel at the same injection timing. A faster ignition, lower premixed spike, and lower peak of combustion pressure were reported for biodiesel compared to diesel when the same mass of fuel was injected. Application of biodiesel resulted in smaller particulate diameter while the use of EGR shifted particulates to large particulate size.

Pereira et al. [125] experimented successfully with soybean biodiesel and its blends with diesel for electrical energy generation. The power generated reported to be same for biodiesel (1593 W) and diesel (1584 W), while fuel consumption increased by 4% with biodiesel. However, the lowest consumption of fuel was obtained with the mixture B20 (20% soybean biodiesel and 80% diesel). Biodiesel exhibited decreased emission of CO by 10%, NO_x by 9% and SO_2 by 53% and increase in CO_2 emission by 22%.

The combustion characteristics and emissions of two different diesel fuels (No. 1 and No. 2) and soybean oil biodiesel were compared at steady state conditions in a four-cylinder turbocharged DI diesel engine at full load at 1400 rpm engine speed [126]. The experimental results revealed that biodiesel provided significant reductions in PM, CO and unburned HC, in contrast to the NO_x emission increased by 11.2% in comparison to diesel operation. An increase of 13.8% in BSFC with biodiesel was also reported. Similar trend of reduction in emissions using blends of methyl and isopropyl esters of soybean oil with No. 2 diesel fuel were reported at several steady-state operating conditions in a four-cylinder turbocharged diesel engine. While fuel consumption was reported to be more with biodiesel than diesel and similar BTE was found for both fuels [127]. Moscherosch et al. [128] demonstrated 15% increase in BSFC, reduction in NO_x emissions by approximately 16% for each start of injection (SOI) test point with soy methyl ester compared to diesel on a turbocharged direct injection diesel engine. The reported ignition delay for B100 and B20 were on average 8.4% longer than the ignition delay for the diesel at an intake oxygen concentration of 16%.

3.2.3. Palm oil

Palm oil has lower production costs [129] and is used both for edible and non-edible purposes. It is mainly grown in South East Asia (Malaysia, Indonesia etc.) and harvested throughout the year. Palm oil contains about 40% each of palmitic acid and mono-unsaturated oleic acid. Other constituents are linoleic acid (10%) and stearic acid (5%). Because of the presence of high level of palmitic and oleic acids, palm oil is rather more saturated. Crude palm oil (CPO) is naturally preserved against oxidation owing to its high level of natural antioxidant (tocotrienols). It is solid at room temperature and cannot be stored and pumped without appropriate heating of tanks and pipes. The viscosity of palm oil is about 10 times higher than diesel at room temperature [130].

To lower CPO viscosity to the level of diesel's viscosity, a heating temperature of at least 92 °C is needed. Bari et al. [130] have shown that heating CPO up to 100 °C not only reduces the viscosity of CPO close to diesel but also provided smooth fuel flow and prevents fuel filter clogging without affecting injection system. The study also revealed that CPO produced a higher peak pressure of 6%, a shorter ignition delay of 2.6°, a lower maximum heat release rate and a longer combustion period compared to

diesel. For the complete load range, the emissions of average CO and NO produced from combustion of CPO were 9.2 and 29.3% higher, respectively, than those produced from combustion of diesel.

The effect of using CPO and its blends (25, 50 and 75%) as fuel on the performance of CI engine was studied by Yusaf et al. [131] using direct-injection, stationary diesel engine at variable engine speeds (1000 rpm through 3000 rpm) under fixed throttle opening. The fuels were preheated to about 60 °C before the injection. For engine speeds lower than 2000 rpm, the blends exhibited higher torque and power output, while the BSFC was found to be higher than the diesel. CPO enhanced the BSFC at higher engine speeds (above 2000 rpm). The blend fuels exhibited lower emissions of NO_x and higher emission of CO as compared to the diesel. The authors have suggested that the lower blends of diesel and CPO (up to 50%) by volume can be utilised as fuel for an unmodified diesel engine without adversely affecting the performance of the engine.

Kalam and Masjuki [132]carried out experiment to evaluate exhaust gas emissions and deposit characteristics of a small diesel engine when operated on preheated crude palm oil (CPO) and its emulsions with 1, 2 and 3% water. The investigation showed that preheating CPO reduced exhaust emissions such as CO, HC and PM as compared to diesel and CPO emulsified fuels. However, preheated CPO increased NO_x emission compared to other fuels. The analysis of deposit characteristic revealed that preheated CPO produced similar volatile fraction, lowest fraction of fixed carbon and highest fraction of ash carbon as compared to diesel and emulsified fuels. Almeida et al. [133] have successfully shown that a diesel-generator set can be adapted to run with palm oil. Preheating the palm oil, the performance and endurance of the diesel generator was found better compared to operation in ambient condition. The emissions of CO and HC were found to increase while that of NO_x deceased. The deposits on the cylinder head were similar to diesel when heated at 100 °C. However, some engine modifications are required to improve lubricating oil degradation, performance, emissions and to reach a more efficient combustion.

An experimental study was conducted to evaluate the suitability of palm methyl ester (PME) for on-road uses of a light-duty diesel engine [134]. In the first phase of experiment, for the whole operational range, the influence of engine speed and load on performance and emissions of engine fuelled with neat PME (B100) and a B50 PME–diesel blend were identified and compared with diesel. While in the second phase, the on-road effect of PME content was studied, when blended with diesel. With neat PME, conclusive reduction of tailpipe NO, UHC and smoke opacity was observed, culminating in a maximum decrease of 5.0, 26.2 and 66.7%, respectively. However, palm methyl ester has insignificant effect on emission of CO. Kalam and Masjuki [135] conducted experiments with mixing anticorrosion additive in palm oil biodiesel to analyse the effect on diesel engines performance, emissions and wear characteristics and observed that fuel consisting 50 ppm anticorrosion/corrosion inhibitor with 15% palm oil biodiesel and 85% diesel not only increases BP but also reduces exhaust emission and wear of metals. With POME, fuel consumption by volume was comparable to that of diesel with marginal difference in engine performance.

3.2.4. *Sunflower oil*

Sunflower, native to North America grows in many areas of the US, Italy, Egypt, Afghanistan, India, China, Russia and throughout Europe. The oil seeds generally are black and have thin hull that cover the kernel. The oil content generally vary from 38 to 50%and is a major source of vegetable oil in the world.

Preheated crude sunflower oil (PCSO) was tested for combustion and emission properties against diesel in a naturally aspirated, indirect injection (IDI) engine [136]. Comparing the combustion characteristics, it was found that the cylinder gas pressure and heat release curves for PCSO were similar to those of diesel. In the case of PCSO, on an average, the reported ignition delay was observed 2.08°C rank angle (CA) longer than diesel and the start of injection timing was advanced by 1.08°CA. For PCSO, nearly 1.36% decrease in the average brake torque, 5% increase in the BSFC and 1.06% increase in thermal efficiency compared to diesel were reported. The emission test results revealed that use of PCSO, on average, decreased unburned HC, CO_2 emissions and smoke opacity by 34, 2.05 and 4.66%, respectively, but increased CO emission by 1.77%. Karaosmanoglu et al. [137] conducted long term engine test of sunflower oil at a speed of 1600 rpm under part load condition for 50 h on a single cylinder direct injection, air cooled diesel engine without encountering any significant problem. No appreciable change was reported in lubrication oil characteristics. The experimental results indicated no significant change in power produced and fuel consumed.

The durability test for methyl ester of sunflower oil as fuel was conducted on four-cylinder diesel engine [138]. The engine was operated for 321 h with diesel and 283 h with methyl ester. Some starting problems were encountered while using methyl ester of sunflower oil while no deterioration was found in the injection system, though some dilution of lubrication oil was also observed. A 5.3% lower energy delivery was observed for sunflower biodiesel resulting in lower power output and exhaust gas temperature. It has been concluded that the sunflower methyl ester successfully completed the 200-h EMA durability test cycle. Rakopoulos et al. [139] have experimentally investigated sunflower and cottonseed oil methyl esters (biodiesels) fuel with blends of 10 and 20% of biodiesels in diesel, in a six-cylinder, turbocharged and after-cooled, direct injection (DI), diesel engine, with the engine working at two speeds of 1200 and 1500 rpm, and at three loads of 20, 40 and 60% of the full loads. Reduction in soot, CO emission and smoke were reported while using biodiesel. Use of all biodiesel blends increased the NO_x emissions, and this emission reported to increase with the increasing percentage of biodiesel in the blends. SFC for biodiesel blends reported to be little higher than that of diesel. However, thermal efficiency did not alter noticeably for all biodiesel blends. Hasimoglu et al. [140] studied low heat rejection (LHR) engine for improving engine performance when sunflower biodiesel is used as an alternative fuel. The results showed that SFC and the BTE were improved and EGT before the turbine inlet was increased for both fuels in the LHR engine.

3.2.5. *Rice bran oil*

The layer between rice and the outer husk of the paddy is known as Rice bran. Rice bran oil (RBO) is an imperative byproduct of milling of rice. It is not a traditional source of edible oil as the other edible oils such as soybean, sunflower, cotton etc. China is largest producer of RBO with total potential of about 6,000,000 t/year. The rice bran in general contains 16–32% of oil by weight. RBO is considered to be one of the most nutritious oils. Free fatty acid (FFA) content in RBO is much higher than other edible oils. RBO offers significant potential not only as a low-cost feedstock, but also as an alternative for biodiesel production [141]. Presence of active lipase in rice bran and lack of economical stabilisation methods, make most of the RBO produced is not of edible grade [142].

The impact of different blends of biodiesel fuels derived from rice bran oil on the atomization and combustion characteristics were investigated utilising a common-rail engine system. The results showed that the presence of biodiesel in the blends

reduced the ignition delay and consequently higher peak combustion pressure was recorded. Also, little difference was reported regarding spray tip penetrations of all the tested fuels. Biodiesel provided reduction in HC emission up to 55% whereas NO_x emissions were increased [143]. Agarwal et al. [144] investigated the effect of using biodiesel and EGR simultaneously on the emissions of all regulated pollutants from diesel engines. A 20% biodiesel blend with 15% EGR was found to be optimum combination for biodiesel, which improved the thermal efficiency, reduces the exhaust emissions and the BSEC. Agarwal and Dhar [145]evaluated the performance, emission, and combustion characteristics of a 4-stroke, four-cylinder, direct-injection transportation diesel engine using 20% blend of rice bran oil (RBO20), and 20% blend of rice bran oil methyl ester (RBOME20) with mineral diesel. The reported results showed that at higher speed, BSFC for RBOME20 was better than diesel. HC and CO emissions for both RBO20 and RBOME20 were lower than mineral diesel. NO_x emissions were comparable for all tested fuels. CO_2 emissions for RBO20 were slightly higher than diesel and RBOME20 and latter have similar emission. As expected, diesel exhibited higher igniton delay than other fuels. Sinha and Agarwal [146] have demonstrated with the long-term endurance test that biodiesel could be successfully used for partial substitution of mineral diesel with less carbon deposit and less wear compared to diesel.

3.2.6. Rapeseed oil

Hazar and Aydin [147] studied two fuel blends with mixture of 20 and 50% rapeseed oil in diesel fuel in a CI engine to investigate the effects of preheated fuel on engine performance and emissions. The tests showed that the power increment for the blends remains lower as compared to diesel fuel. Although the mass of fuel consumptions for blends were higher than those of diesel, preheating reduced mass of fuel consumption. NO_x increased with preheating and increase in percentage of SVO in the blends. Emissions of CO and smoke decreased with preheating. It has been concluded that preheating SVO marginally affected engine performance but significantly reduces exhaust emissions.

Labeckas and Slavinskas [148] have presented the comparative bench testing results of a naturally aspirated, 4-stroke, four cylinder, water cooled, direct injection diesel engine operating on diesel fuel and cold pressed rapeseed oil. Operating with rapeseed oil, at full load condition, test results revealed that the BSFC at the maximum torque and rated power was higher than that for diesel fuel by a value of 12.2 and 12.8%, respectively. However, the BTE of both fuels did not differ greatly. With rapeseed oil, a large reduction about 27–35% in smoke was observed at a fully opened throttle condition. Preheating of rapeseed oil ensured a smooth flow through the fuel filter and reduced the BSEC. However, there is a need for long-term endurance tests before commercial use of crude rapeseed oil. While testing rapeseed methyl ester and its blends in a high speed, air-cooled, indirect injection diesel engine, it has been observed that increase in the emission of CO_2 and significant reduction in emissions of hydrocarbon (HC) with RME and its blends compared to diesel fuel [149]. At light load condition diesel produced the lowest CO emissions but produced the highest emissions at higher load. Slight reduction in the fuel economy was observed with RME while no significant difference was noticed for the exhaust temperatures of all the tested fuels particularly at high speed operations. An oil dilution with biodiesel was reported using lubricating oil analysis after 33 h. Jeong et al. [150] showed that the use of rapeseed biodiesel was associated with higher BSFC and lower smoke density around 26.05–28.73% than diesel. However, biodiesel and its blends increased the emission of CO, CO_2, and NO_x, to a larger extent than was observed with diesel. Tsolakis et al. [151] tested rapeseed methyl ester (RME) and different RME blends with diesel on the naturally aspirated, air-cooled, single-cylinder direct injection diesel engine. The combustion of fuels (RME, B20 and B50) in an unmodified engine resulted in reduction in ignition delay and higher heat release rate in the initial uncontrolled premixed combustion phase causing increased cylinder pressure and temperature. The advanced RME combustion resulted in the reduction of smoke, HC and CO while both NO_x emissions and fuel consumption were increased. It has been suggested that the use of EGR was more effective in the case of biodiesel blends combustion compared to diesel combustion. While conducting exhaust emission tests on rapeseed oil methyl ester (RME), rapeseed oil ethyl ester (REE) and diesel along with their mixtures; Makareviciene and Janulis [152] have shown that REE had less negative impact on the environment than that of RME in terms of CO_2, NO_x and smoke emission as well as biodegradability in aquatic environment. However, both the esters had better emission profile than diesel. One aspect of NO_x emission was noticeable that it increased for higher blends of the esters and pure esters, while decreased for lower.

3.3. Waste oil

Used cooking or frying oils are of increasing interest as inexpensive feedstock for biodiesel production. They are often discarded by restaurants and similar facilities, and will play a major role in near future. Biodiesel fuel produced from used cooking oil has shown very promising chemical and physical properties; most notably; cetane number and sulphur content.

Pugazhvadivu and Jeyachandran [153] carried out engine performance test on a constant speed, direct injection, single-cylinder, 4-stroke, water-cooled diesel engine test rig. Preheating waste frying oil up to 135 °C brings down its viscosity close to that of diesel at 30 °C. The result indicates that the engine performance is approaching that of conventional diesel by preheating WFO to 135 °C. The engine exhaust emissions such as CO and smoke were reduced considerably. However, these emissions were higher for all tested fuels compared to diesel. While NO_x emission was found lower for all blends. In an experiment using waste cooking oil and diesel (50/50 by volume) as fuel in water-cooled, naturally aspirated, 4-stroke, and direct injection (DI) diesel engine; Abu-Jrai et al. [154] exhibited a considerable reduction in the smoke opacity and unburnt hydrocarbons but an increase in the NO_x emissions. However, EGR resulted in reduction in NO_x emission as expected. For the entire load range (up to 75% of the maximum load), the total combustion duration of the tested fuel was increased as compared to diesel fuel. Advancement in the combustion was also reported. Lin et al. [155] have studied used wasted cooking oil biodiesel and its blends, and diesel to compare the trace formation from the exhaust tail gas of a diesel engine. Lowest CO concentration was reported for B20 among all tested fuels for all engine speeds. B50 produced higher CO_2 than other fuels for all engine speeds, except at 2000 rpm, where B20 emitted the highest CO_2. The biodiesel and its blends produced higher NO_x for various engine speeds. SO_2 formation shows an increasing trend with the increasing percentage of diesel in the blends. For the tested engine speed, the PM concentrations from B100 engines were higher than from other tested fuels. Overall, we may conclude that B20 and B50 are the optimum fuel blends.

The diesel engine performance and exhaust emission analysis using waste cooking oil biodiesel fuel with an artificial neural network (ANN) has been studied in two cylinders, 4-stroke diesel engine [156]. The experimental results revealed that blends

of waste cooking oil biodiesel with diesel fuel provided better engine performance and improved emission characteristics compared to diesel. An ANN model was developed based on standard back-propagation algorithm for the engine. Results confirmed that the ANN model can predict the engine performance and exhaust emissions quite well with correlation coefficient (R) 0.929 and 0.999.

Hirkude and Padalkar [157] carried out experiments on a single-cylinder, 4-stroke, direct injection, diesel engine operated on waste fried oil methyl esters (WFOME) blended with mineral diesel. BTE of the WFOME and its blends were lower than diesel, with a value of 28.02%, B50 was closer to diesel. For WFOME, fuel consumption and EGT were 0.36 kg/kW h and 307 °C as against 0.29 kg/kW h and 291 °C of diesel. For different blends, emission of CO, PM decreased by 21–45% and 23–47% while NO_x emission increased by 4–10% compared to diesel. Murillo et al. [158] studied biodiesel from cooking oil in outboard engine and showed that use of biodiesel resulted in reduction of CO emission up to 12% and increased in NO_x emission up to 20%. However, as an exception, reduction in NO_x emission was reported with B20. Small power reduction (up to 8%) along with small increase in fuel consumption was also reported in the test. Utlu and Kocak [159] tested biodiesel produced from waste frying oil in a diesel engine with turbocharged, four cylinders and direct injection. In comparison to diesel, the test reported increase in SFC by 14.34% and decrease in power by 0.55%. Emission values of CO and NO_x were decreased by 17.14 and 1.45%, respectively. Increase in smoke intensity was on average 22.46%for biodiesel as compared to diesel fuel.

Tests were conducted with ethyl ester of waste vegetable oils and its blends along with diesel to compare the engine performance and exhaust emissions [160]. The results indicated that efficient burning of the tested fuels resulted in lower SFC and hence higher engine thermal efficiency. In terms of emission of CO and unburned hydrocarbons biodiesel and its blends were found better than diesel.

3.4. *Animal fat*

Biodiesel may also be produced from less expensive fats, including inedible tallow, pork lard and yellow grease. Animal fats are highly viscous and mostly in solid form at ambient temperature because of their high content of saturated fatty acids [161]. The tallow methyl ester shows a higher density, kinematic viscosity, cetane number, but a heating value about 7% less than the diesel fuel and causes power loss. Also, the flash point of biodiesel was found lower than diesel—perhaps due to the presence of residual alcohols [162]. Tallow methyl ester has lower pour point, which is about 0 °C. Therefore, it cannot be used as a neat diesel fuel in cold weather conditions. Preheating and lowering freezing point is required to eliminate the problems related with cold weather conditions [163].

Kumar et al. [164] conducted experiment to evaluate the effect of fuel inlet temperature on performance, emission and combustion characteristics of a diesel engine. A single cylinder direct injection diesel engine developing a power output of 2.8 kW at 1500 rpm was tested using preheated animal fat as fuel varying from 30–70 °C. Animal fat at low temperature resulted in higher ignition delay and combustion duration than diesel; however, preheating animal fat reduces these values. Preheating improves the premixed combustion rate. The specific energy consumption was found to be higher with neat animal fat at all temperatures as compared to diesel; however, preheated animal fat showed improvement. EGT was higher with animal fat. Due to low exhaust temperature of diesel, the volumetric efficiency was high. Preheated animal fat reduces smoke levels at all temperatures. At low temperature hydrocarbon and carbon monoxide emissions were higher with animal fat but fuel preheating reduces these emissions. As expected fuel preheating results in increased NO_x emission, although, the level is still lower than diesel.

The engine performance and exhaust emission with tallow methyl ester, petroleum based diesel fuel and its blends were evaluated at different engine speed under full load conditions [163]. The engine performance run by tallow methyl ester and its blends were comparable with the performance run by pure diesel. The effective engine power for biodiesel and blends was less than that of diesel by a value around 2.4–4%. It was also observed that the addition of biodiesel to the diesel fuel decreased the thermal efficiency of engine and increased the SFC The exhaust emissions from biodiesel and its blends, at the range of tests, were lower than that of pure diesel fuel. The lowest CO, NO_x emissions and the highest exhaust temperature were obtained for B20 among all other fuels. Guru et al. [165] studied the effect on engine performance and exhaust emissions while using chicken fat biodiesel with synthetic Mg (Magnesium) additive in a single-cylinder, direct injection (DI) diesel engine. Engine tests were run with diesel fuel and a blend of 10% chicken fat biodiesel and diesel fuel at full load operating conditions and different engine speeds from 1800 to 3000 rpm. The results showed that the variation in engine torque using both the fuels didn't change significantly, while the SFC for biodiesel (10%) increased by 5.2%. In-cylinder peak pressure slightly increased and the start of combustion was advanced for biodiesel blends. CO and smoke emissions were decreased by 13 and 9%, respectively, but NO_x emission increased by 5%. In other experiment, three monoalkyl fatty acid esters namely ethyl greasate, isopropyl tallowate and ethyl tallowate derived from tallow and grease, both neat and 20% blends in diesel were evaluated as prospective diesel engine fuels [166]. Comparing with diesel, esters have shown 1 to 3% higher indicated mean effective pressure, shorter injection durations and increased torque and power. All the three ester-diesel blends showed modest improvement over diesel in carbon build-up characteristics. Reduction in emissions in CO_2 by 0.25 to 0.5% was reported and less than 1% increase in O_2 was found. However, no apparent change in CO, HC, or NO_x was reported. While performing combustion tests for methyl ester of fish oil and its blends with diesel fuel in a DI diesel engine, at constant speed of 1500 rpm under variable load condition showed no major deviations in diesel engine combustion. The BSFC for biodiesel and its blends were little higher than diesel. BTE for B20 was 3% higher compared to diesel. Reduction of main noxious emissions such as CO and HC were found linear with the addition of biodiesel. NO_x emission increased with the addition of biodiesel and found to be more with B100 [167].

3.5. *Other oils*

To study the performance and emission characteristics of engine fuelled with blends (10, 20, 30 and 40% v/v) of pure putranjiva oil and diesel at different injection timings (45, 40, 35° CA bTDC) and at constant compression ratio 20:1 were used in Ricardo variable compression diesel engine. The result transpired that up to 30% blends of pure putranjiva oil and diesel reduce the emissions such as CO, NO_x, smoke, particulates, etc. The performance such as BTE and BSFC were comparable to neat diesel up to 30% blend. However, for higher blends, the BTE and BSFC showed poor quality. Also, putranjiva oil blends yielded better performance at 45° CA bTDC [168].

Anand et al. [169] carried out experiment to evaluate the combustion performance and exhaust emission characteristics of turpentine oil fuel (TPOF) blended with diesel fuel in a diesel

engine. The result showed that the engine operating on turpentine oil and its blend had lower carbon monoxide (CO), unburned hydrocarbons (HC), NO_x, smoke level and particulate matter. Further the results show that the addition of 30% TPOF with DF produced higher BP and net heat release rate. Above 30% TPOF blends, developed lower BP and net heat release rate.

Li et al. [170] experimented with different blends of Eruca Sativa Gars biodiesel in a Fukuda light truck. The fuels were tested at 40 km/h engine speed at engine power ranging from 200 to 2000 N. It was shown that the fuel consumption rates of B100 were higher from 8 to 18% than that of B0 at 200 to 2000 N m. Maximum reduction in CO emissions was 20% with B100 at higher load and HC emission decreased by 33%. Slight increase in CO_2 emission was recorded. Experimental tests have been carried out to evaluate the performance of a 4-stroke 3 cylinder direct injection naturally aspirated engine using croton methyl ester (CME) and its various blends with diesel fuel as fuel [171]. The results show lower BTE and higher EGT for CME compared with the pure diesel fuel. Emissions of CO were reduced at higher loads with the biodiesel. In comparison to diesel, CO, CO_2 and HC emissions were higher for the CME and blends but the smoke emission and NO_x emission were lower. The performance, emission and combustion characteristics of poon oil (*Sterculia foetida*) and its blends with diesel were measured in a single cylinder 4-stroke aircooled diesel engine in order to determine the suitability of poon oil for engine use. The test indicated that when blended with diesel especially up to 20%, poon oil presented lower viscosity, improved volatility, better combustion and less carbon deposit. It was found that there was a reduction in NO_x emission for poon oil (30%) and its diesel blends along with a marginal increase in HC and CO emissions, except 20%blend, with which HC emission decreases by 14% and CO emission by 12%. Brake thermal efficiency was found lower for neat poon oil and its diesel blends [172]. Mbarawa [173] evaluated clove stem oil and diesel blends (25 and 50%) in a four cylinder, 4-stroke, naturally aspirated, water cooled, direct injection diesel engine. Comparing with the diesel, slight decrease in power along with increase in fuel consumption and decrease in BTE were reported. With the emission point of view, CO, HC emissions were lower and smoke reduces drastically. NO_x emission increased sharply specially with 50% blend. Deshmukh and Bhuyar [174]conducted tests on a double cylinder, direct injection, CI engine using balanties methyl ester and diesel. From the engine tests, compared to diesel, increase in BSFC (6.8% approximately) combine with slight decrease in BTE and slight increase in EGT were observed. Emission levels (HC, CO, NO_x and smoke) were lower for BME. However, at higher load the emission level of NO_x for biodiesel was higher. Mallikappa et al. [175] demonstrated that utilisation of cardanol biodiesel blended with diesel resulted in reduction of BTE and increase in BSEC especially at high load. Increase in NO_x and CO emission was also reported with biodiesel. However, up to 20% blends, HC and smoke emission was comparable with the diesel. Gumus and Kasifoglu [176] tested apricot seed kernel oil methyl ester and its blends with diesel fuel in a CI diesel engine. The results indicated increase in power initially (up to B20) with increasing percentage of biodiesel in the blend, however, further increased in concentration of biodiesel reduced power. BTE also exhibited the same trend and reversed trend for the BSEC. B20 blend emitted least CO_2. Biodiesel emitted the lowest level of CO_2, HC and CO emissions but emitted highest NO_x among all tested fuels. Gumus [177] reported that when diesel engine was run with biodiesel from hazelnut kernel oil as fuel, it produced equivalent power to that of the diesel fuel. The above discussion of performance and emissions of different biodiesel are summarised in Table 2. The table shows the trend in the variation in BP, SFC, BTE and emissions such as NO_x, CO, CO_2, HC and smoke.

4. Discussion

Fats and oils are hydrophobic substances in the plant and animal composed primarily of the fatty esters of glycerol, so-called triacylglycerides. On the basis of their chemical structure, triglycerides can be classified as saturated, monounsaturated or polyunsaturated. Fatty acid composition of different vegetable oils and esters are given in Tables 3 and 4. Fully saturated triglycerides such as coconut oil are solid at room temperature and thus are difficult to use as fuel, whereas excessive carbon deposits in engine are reported when polyunsaturated triglycerides like rapeseed oil are used as fuel. Vegetables oils are mostly unsaturated; thus they are more susceptible to oxidation and thermal polymerization reaction. The oxidation resistance of oils is more markedly affected by the fatty acid composition [193]. Many attempts are made to use pure vegetable oils in CI engines. Generally operational and durability problems are encountered while using straight vegetable oils as fuel. Starting ability, combustion, ignition and performance comes under operational problems while durability problems are related to carbonization of injector tip, deposition formation, lubricating oil dilution and ring sticking. Triglycerides exhibit low volatility due to their higher molecular weights than diesel. The viscosity of vegetable oil is almost 10 times higher than diesel fuels [30,39,194]. Poor cold flow properties, low volatility along with oxidative stability are main hurdles in the utilisation of SVO in diesel engine. The combined effect of high viscosity and low volatility of vegetable oils are poor cold engine start up, misfire and ignition delay [187]. To reduce these problems and to decrease viscosity, different methods have been adopted; namely, blending, microemulsion, transesterification, preheating and pyrolysis (thermal cracking). Of these, transesterification is the most common method. Transesterification also improves the cold properties of biodiesel [195]. Methanol is the most preferred alcohol used to produce biodiesel because of its low price, and its physical and chemical advantages, as it has polar and the shortest chain [196]. Although, transesterification makes the fuel properties of vegetable oils closer to diesel, the viscosity of the biodiesel remains still higher (about 2 times) than that of diesel. Further decrease in viscosity can be achieved through blending or heating [192].

4.1. Effect of fatty acid on properties of biodiesel

The transesterification reaction of an oil or fat produces biodiesel fuel corresponding to the fatty acid profile of its parent oil or fat. Thus, biodiesel can be said to be a mixture of fatty esters with each ester component contributing to the properties of the fuel. In this section, discussion has been carried out about properties of biodiesel in relation with the fatty acid structure. Properties of biodiesel like ignition quality, cold flow, oxidative stability, viscosity, and lubricity are strongly influenced by the structure of its component fatty esters and the nature of its minor components. These properties are critical for the operation of a fuel in a diesel engine. The properties of different vegetable oils and biodiesels are given in Table 5. Broad range of value of properties of the same biodiesel reported by different researcher is probably caused by differences in the fractional conversion of triglycerides to esters and by the presence of residual methanol and glycerol in the fuel. The standard properties of biodiesel as per ASTM and European standard are given in Table 6 [197,213,].

The cetane number of biodiesel derived from different feedstock, reported in different literatures, ranges from 48 to 65. The variation in reported cetane number arises mainly due to chemical structure, oil processing technology and climate condition of the area where oil is collected [214]. Wadumesthrige et al. [215] have demonstrated that not only the composition of biodiesel influence

Table 2
Summary of effect of biodiesel on performance and emission.

Author	Reference	Fuels	Effects	BP	BSFC	BTE	EGT	CO	CO_2	NOx	smoke	HC
Jo-Han Ng, et al.	134	Palm methyl Ester	Increasing speed	na	na	na	na	⇧	⇧	⇧	⇨	⇧
			Increasing Load	na	na	na	na	⇩	⇧	⇧	⇧	⇩
Kalam, et al	132	Preheated palm oil	Running time	na	na	na	na	⇩	⇩	⇧	pm ⇩	na
		Emulsified palm oil	Running time	na	na	na	na	⇧	⇧	⇩	pm ⇧	na
Bari et al	130	Preheated palm oil	Increasing Load	na	*⇨	*⇨	na	⇧	na	⇧	na	na
Yusaf et al.	131	Blends of Palm oil	Low speed	⇧	⇧	na	⇩	⇧	na	⇩	na	na
			High speed	⇩	⇩	na	⇨	⇩	na	⇨	na	na
Agarwal et al.	13	Karanj oil and lower blends preheated and unheated	Increasing Load	na	⇩	⇧	⇧	⇩	na	⇩	na	⇩! / ⇧
		Karanj oil higher blends preheated and unheated	Increasing Load	na	⇩# / ⇧	⇧# / ⇩	⇧	⇧	na	⇩	⇧	⇩! / ⇧
Sureshkumar et al.	87	Pongamia pinnata methyl ester lower blends	Increasing Load	na	⇩	na	⇩	⇩	⇧! / ⇩	⇩	⇧	Negligible
		Pongamia pinnata methyl ester higher blends		na	⇧	na	⇩	⇩	⇩	⇩	na	Negligible
Srivastava et al.	88	Karanja methyl ester	Increasing Load	na	⇧	⇩	na	⇧	na	⇧	na	⇧
		KMEwithblendsup to 20%		na	⇧	⇩	na	⇩	na	⇧	na	⇧
Almeida et al.	133	Preheated palm oil		na	⇧	na	⇧	⇧	⇨	⇩	na	⇧
Baiju et al.	89	methyl and ethyl esters of Karanja oil	Increasing Load	na	⇧	⇩	na	⇧	na	⇩	⇩	na
Ozsezen et al.	136	preheated crude sunflower oil		⇩	⇧	⇧	na	⇧	⇩	na	⇩	⇩
Rakopoulos et al.	139	sunflower and cottonseed methyl esters	two speeds and three loads	na	⇧	⇨	na	⇩	na	⇧	⇩	na
Hasimoglu et al.	140	Sunflower methyl ester		⇧	⇧	⇧	⇩	na	na	na	na	na

Table 2 (*Continued.*)

Author	Reference	Fuels	Effects	BP	BSFC	BTE	EGT	CO	CO_2	NOx	smoke	HC
Pryor et al.	120	Crude Soybean oil		⇨	⇧	⇧	na	⇩	⇧	na	⇩	⇩
Qi et al.	122	Soybean methyl ester	Increasing speed	⇨	⇧	na	na	⇩	na	⇩	⇩	⇩
Canakci	126	Soybean biodiesel B20	Full load at 1400 rpm	na	⇧	⇨	na	⇩	⇨	⇧	⇩	⇩
		Soybean biodiesel B100		na	⇧	⇧	na	⇩	⇧	⇧	⇩	⇩
Puhan et al.	108	methyl ester (Mahua oil)	Increasing power	na	⇧*	⇧	⇧	⇩	⇧	⇧	na	⇩
		Ethyl ester (Mahua oil)		na	⇧	⇨	⇧	⇩	⇧	⇩	na	⇩
		Butyl ester (Mahua oil)		na	⇧	⇩	⇧	⇩	⇧	⇩	na	⇩
Godiganur et al.	106	methyl ester of mahua oil and its blends (except B20)	Increasing power	na	⇧	⇩	⇧	⇩	na	⇧	na	⇩
		B20 ester		na	⇧	⇧	⇧	⇩	na	⇧	na	⇩
Puhan et al.	107	mahua oil ethyl ester	Increasing Load	na	⇧	⇨	⇧	⇩	⇧	⇩	⇩	⇩
Raheman et al.	103	mahua oil methyl ester and its blends (except B20)	Increasing Load	na	⇧	⇩	⇧	⇩	na	⇧	⇩	na
		B20		na	⇧	⇩! / ⇧	⇧! / ⇩	⇩	na	⇧	⇩	na
Hazar et al.	147	Preheated rapeseed oil with 20% and 50% blends	Increasing Speed	⇩	⇧	⇨	⇧	⇩	⇨	⇩	⇩	⇨
Nwafor et al.	149	rapeseed methyl ester and its blends	Increasing Load at two speeds	na	⇧	na	na	⇧! / ⇩	⇧	⇩	na	⇩
Tsolakis et al.	151	Rapeseed methyl ester and blends	Without EGR	na	⇧	⇩	na	⇩	na	⇧	na	⇩
			With EGR	na	⇧	⇩	na	⇧	na	⇨	na	⇩
Abu-Jrai	154	Waste cooking oil Biodiesel (B50)	Increasing speed	na	⇧	⇩	na	na	⇧	⇧	⇩	⇩
Ghobadian et al.	156	Waste cooking oil Biodiesel (B10 - B50)	Increasing load	⇨	⇧	na	na	⇩	na	na	na	⇩
Pugazhvadivua et al.	153	Preheated waste cooking oil (30^0C, 75^0C, 135^0C)	Increasing load	na	⇧	⇩	na	⇧	na	⇩	⇧	na
Karabektas et al.	90	preheated cottonseed oil methyl ester	Increasing speed	⇩	na	⇧	na	⇩	na	⇧	na	⇩

Nabi et al.	91	cottonseed oil methyl ester	Increasing speed	na	⇧	⇩	na	⇩	na	na	⇩	⇩
Aydin et al.	92	cottonseed oil methyl ester & blends	Increasing speed	⇩	⇧	na	na	⇩	na	⇩	⇩! / $ ⇧	na
Oner et al.	163	Tallow methyl ester and its blends	Increasing speed	⇩	⇧	⇩	⇧	⇩	na	⇩	⇩	na
Metin Gu¨ ru	165	chicken fat biodiesel B10	Increasing	⇨	⇧	⇩	na	⇩	na	⇧	⇩	na
Kumar et al.	164	Preheated animal fat (30-40-50-60-70)	Increasing	na	na	na	⇧	⇧ ⇩	na	⇩	⇩	⇧
Godiganur et al.	167	Fish oil methyl ester and its blends	Increasing load	na	⇧	⇩ / !! ⇧	⇧	⇩	na	⇧	na	⇩
Panwar et al.	178	castor methyl ester blends B5,B10,B20		⇧	⇩ / !! ⇧	⇧	⇧$	na	na	⇧$	na	na
Kalam et al.	116	Coconut oil and its blends	Increasing concentration	⇧$$	⇧	na	⇩	⇩	⇧	⇩	⇩	⇩
Lin et al.	141	Rubberseed methyl ester	Increasing speed/ Load	⇩	⇧	na	na	⇩	na	⇩	na	⇩
Forson et al.	81	blends of jatropha	Increasing Torque	⇧	⇧	⇧	na	na	⇧	na	na	na
Chauhan et al.	83	Jatropha methyl ester and its blends	Increasing load	na	⇧	⇩	⇩	⇩	⇧	⇧	na	⇩
Rao et al.	85	Jatropha methyl ester and its blends	Increasing load	na	⇧	⇩	⇧	⇩	na	⇧	na	⇩
Haldar et al.	168	Putranjiva roxburghii oil and blends	Increasing load	na	⇧	⇩	⇩	⇩	na	⇧! / ⇩	⇩	⇩
Aliyu et al.	171	Croton methyl ester (CME) and its blends	Increasing speed	na	⇧	⇩	⇧	⇧! / ⇩	na	na	na	na
Devan	172	poon oil and its blends	Increasing load	na	⇧	⇩	⇧	⇧$ / ! ⇩	⇩	⇩	⇧ / !! ⇩	⇧ / !! ⇩
S.J.Deshmukh	174	Balanites methyl ester	Increasing load	na	⇧	⇩	⇧	⇩	na	⇩! / $ ⇧	⇩	⇩

Preheated, ^ Unheated, ! Lower Load, !! for B20.
[*]With increasing temperature.
[**]Total Fuel Consumption.
[a]Higher load.
[b]High speed.
[c]Beyond 50̄ C.

Table 3
Fatty acid compositions of vegetable oils.

Oils	< C10:0	C12:0	C14:0	C14:1	C15:0	C16:0	C16:1	C17:0	C18:0	C18:1	C18:2	C18:3	C18:1OH	> C20:0
Coconut oil [113]	14	51.0	18.5	–	–	7.5	–	–	3.0	5.0	1.0	–	–	–
Palm [185]	–	0.1	1.0	–	–	42.8	–	–	4.5	40.5	10.2	0.2	–	–
Beef tallow [186]	–	–	3.1	1.3	0.5	23.8	4.7	1.1	12.7	47.2	2.6	0.8	–	–
Lard [186]	–	–	1.3	0.0	0.0	23.5	2.6	0.4	13.5	41.7	10.7	0.0	–	–
Yellow grease [182]	–	–	2.43	–	–	23.24	3.79	–	12.96	44.32	6.97	0.67	–	–
Brown grease [182]	–	–	1.66	–	–	22.83	3.13	–	12.54	42.36	12.09	0.82	–	–
Cottonseed [139]	–	–	0	–	–	28	–	–	11	13	58	0	–	–
Peanut [187]	–	–	0.0	–	–	11	–	–	2	48	32	1	–	3
Soybean [100]	–	–	0.0	–	–	13.9	–	–	2.1	23.2	56.2	4.3	–	–
Corn [187]	–	–	0.0	–	–	12	–	–	2	25	6	Tr	–	Tr
Sunflower [100]	–	–	0.0	–	–	6.4	–	–	2.9	17.7	72.9	0.0	–	–
Sunflower [139]	–	–	0.0	–	–	6	–	–	3	17	74	0	–	–
Safflower [185]	–	–	–	–	–	7.3	–	–	1.9	13.6	77.2	–	–	–
Rapeseed [100]	–	–	0.0	–	–	3.5	–	–	0.9	64.1	22.3	8.2	–	–
Jatropha [179]	0.1	–	0.1	–	–	15.1	0.9	–	7.1	44.7	31.4	0.2	–	0.4
Jojoba [184]	–	–	–	–	–	16	–	–	6.5	43.5	34.4	0.0	–	–
Linseed [100]	–	–	0.045	–	–	6.21	–	–	5.63	20.17	14.93	51.12	–	–
Madhuca indica [100]	–	–	0.09	–	–	19.93	–	–	25.96	37.21	14.74	0.28	–	–
Chicken fat [183]	–	–	0.50	–	–	24.00	5.80	–	5.80	38.20	23.80	1.90	–	–
Karanja [89]	–	–	–	–	–	11.65	–	–	7.5	51.59	16.64	0.0	–	–
Castor oil [180], [181]	–	–	0.01	–	–	0.7	–	–	1.85	2.8	4.4	0.2	90.2	–
Rubberseed [185]	–	–	–	–	–	10.2	–	–	8.7	24.6	39.6	16.3	–	–
Sesame [185]	–	–	–	–	–	13.1	–	–	3.9	52.8	30.2	–	–	–
Mahua [185]	–	–	–	–	–	24.2	–	–	25.8	37.2	12.8	–	–	–
Poon oil [172]	–	–	–	–	–	22.4	–	–	7.3	16.42	45.89	6.47	–	–
Balanites oil [174]	–	–	–	–	–	17	4.3	–	7.8	32.4	31.3	7.2	–	–
Tall oil [186]	–	–	–	–	–	1.28	–	–	3.8	58.75	32.63	2.16	–	–

Table 4
Fatty acid composition of esters.

Oils	C8:0	C10:0	C12:0	C14:0	C16:0	16:1	C16:2	C17:0	C18:0	C18:1	C18:2	C18:3	C20:0	C20:1	C20:2	C20:4	C20:5	C18:1OH	C22:0	C22:1
Rapeseed oil ME [188]	–	–	0.00	0.1	4.6	0.3	–	–	1.8	60.7	19.1	8.3	–	–	–	–	–	–	–	–
Rapeseed oil ME [5]	–	–	–	–	5.2	–	–	–	1.4	66	18.9	5.6	1.9	–	–	–	–	–	1	–
Corn oil ME [192]	–	–	–	–	11.4	–	–	–	1.3	27.1	60.2	–	–	–	–	–	–	–	–	–
Peanut oil ME [192]	–	–	–	–	17.2	–	–	–	2.7	40.5	36.6	0.5	0.9	–	–	–	–	–	1.5	–
Sunflower oil ME [192]	–	–	–	–	4.9	–	–	–	2.3	32.6	59.4	–	–	–	–	–	–	–	0.5	–
Palm kernel ME [192]	3.6	3.1	48	14.7	11.5	–	–	–	1.4	15.9	1.8	–	–	–	–	–	–	–	–	–
Palm oil ME [192]	–	–	0.5	1.6	49.8	–	–	–	2.9	38.6	6.6	–	–	–	–	–	–	–	–	–
Palm oil ME [188]	–	–	0.2	1.1	43.0	0.2	–	–	4.7	40.1	9.5	0.2	–	–	–	–	–	–	–	–
Jatropha oil methyl ester [188]	–	–	0.0	0.0	12.6	0.8	–	–	5.9	35.8	28.8	0.2	0.2	–	–	–	–	–	–	–
Soybean oil ME [5]	–	–	–	–	11.7	–	–	–	3.97	21.27	53.7	8.12	1.23	–	–	–	–	–	–	–
Soybean oil ME [189]	–	–	–	0.29	14.16	1.27	0.24	–	5.19	48.20	22.19	1.45	0.28	–	–	–	–	–	–	–
Tallow oil ME [188]	–	–	0.0	1.2	18.9	2.1	–	–	8.9	44.4	15.7	2.8	0.3	–	–	–	–	–	–	–
Castor oil ME [189]	–	–	–	–	0.86	–	–	–	1.01	2.63	4.1	0.36	0.16	0.25	–	–	–	89.54	–	–
Marine fish oil ME [190]	–	–	–	3.16	19.61	5.16	–	1.82	5.24	20.94	2.69	0.90	4.75	–	0.81	2.54	3.70	–	1.55	0.98
WVO ME [192]	–	–	1.6	1.5	27.3	–	–	–	4.9	36.1	25.7	1.9	–	–	–	–	–	–	–	–
WVO BD [190]	–	–	–	0.54	14.18	0.74	–	0.17	3.77	47.51	24.83	4.97	0.8	–	0.17	0.38	0.03	–	0.1	0.18
Salmon oil BD [190]	–	–	–	5.08	15.39	7.55	–	0.46	4.00	20.76	3.78	0.99	0.15	–	0.30	2.08	9.49	–	0.09	–

the cetane number but oxidative aging also affect cetane number and showed that derived cetane number increases with oxidation depending upon the conditions of oxidation. Cetane number of biodiesels decrease with increasing unsaturation (chemical structure) and increases with increasing chain length. One long straight chain is enough to impart a high cetane number although the other moiety is branched. Alcohol utilised in producing biodiesel also affect the cetane number. Branched esters derived from alcohols such as iso-propanol have cetane numbers competitive with methyl or other straight chain alkyl esters [3,20,216]. Canakci et al. [217] have shown that saturated compounds like myristic acid (C14:0); palmitic acid (C16:0); stearic acid (C18:0) have higher

cetane number. Further they tend to crystallise indefensibly with variation of temperature. Knothe et al. [218] have shown that the reason for lower CN of some fatty compounds is due to the formation of low-CN compounds during pre-combustion, especially for more unsaturated esters. Biodiesel prepared from more saturated oil such as those prepared from tallow and used frying oil has higher cetane number.

The carbon/hydrogen ratio of biodiesels from different sources will be slightly different, in accordance with the degree of unsaturation. Unlike diesel, biodiesel contains around 10–12% oxygen by weight, causing lower heat of combustion and reduces the particulate emission. The heat of combustion or calorific value of a fuel is an important measurable parameter as it shows the amount of heat liberated by the fuel within the engine that enables the engines to do the work. Further, it is the indication of the energy chemically bound in it. Calorific value is the most important property of a fuel which determines the energy value of it [219]. In general, heat of combustion increases with the chain length.

Cold flow properties such as cloud points and pour points are the major problems associated with the use of biodiesel. The cold flow properties of biodiesel fuels depend on the feedstock (specific type of oil, fat or grease etc.) from which they are made and are a strong function of the level of saturated fat [220]. Due to their much lower melting point, unsaturated esters act as solvents, with the saturated esters dissolved in it. Thus, with decreasing temperature, saturated fatty compounds in a mixture crystallize at higher temperature than the unsaturated compound [221]. It is the reason, biodiesels with significant amounts of saturated fatty compounds exhibits higher cloud point and pour point. Animal fats, palm and coconut oils are more highly saturated and thus have higher CN, higher cloud point as shown in Table 5. The presence of solid crystals in the biodiesel affects its viscosity, volatility, flow ability and filterability. In addition, esters of branched chain alcohol also improve cold flow properties [222].

Viscosity and density are two key fuel properties parameters required by biodiesel and diesel fuel standards. Pratas et al. [223] measured densities and viscosities for seven ethyl esters and eight methyl esters at atmospheric pressure and temperatures from 273.15 to 363.15 K.The results show that the viscosity of all esters increases with the ester chain length (number of carbon atoms) and decreases with its level of unsaturation. This relation holds also for the alcohol moiety, as for equivalent fatty acid composition the ethyl esters exhibited a higher viscosity than the corresponding methyl ester. The kinematic viscosity of unsaturated fatty compounds achingly influence by the nature and number of double bonds, while the effect of double bond is less. Viscosity is also affected by double bond configuration, *cis* double bond configuration giving a lower viscosity than trans. Free fatty acids or compounds with hydroxy groups possess significantly higher viscosity [224]. Viscosity and spray penetration is higher for biodiesel compared to diesel. This is attributed mainly to the high viscosity of biodiesel which prevents the breaking of the spray jet, resulting in an increase in the size of the spray droplets. The larger the size of the spray droplets, the higher the momentum and, hence, smaller the resistance preventing penetration [225]. Density is notable properties of fuel because injection systems, pumps, and injectors must deliver the amount of fuel precisely adjusted to provide proper combustion [226]. On the basis of an accurate knowledge of biodiesel density, the estimation of other properties such as the cetane number, whose direct measurement is complex and presents low repeatability and low reproducibility, can be achieved [227]. Despite the higher density of biodiesel compared to diesel, energy content of which is lower both on a mass and a volume basis compared to diesel fuel. Thus more fuel injected into the combustion chamber in order to gain the same power as the diesel from the engine. This is the reason for the increase in fuel consumption for biodiesel [215].

Iodine number is a measure of the degree of unsaturation of the fuel [208]. Goinath et al. [207] has shown that an increase in unsaturation increases the number of double bonds which increases the iodine number. Unsaturation can lead to deposit formation and storage stability problems with fuels. Oxidative stability refers to the autoxidation of the double bonds in the tail-group of the fatty acid chains of biodiesel. Autoxidation of biodiesel occur due to prolong exposure to air during storage. This can adversely alter fuel quality by affecting properties such as kinematic viscosity, acid value and peroxide value. Hence, the long-term storage stability of biodiesel can be correlated with the number and position of double bonds [228]. The presence of polyunsaturated fatty esters is the cause of oxidative stability problems with biodiesel [229]. The positions allylic to double bonds are especially susceptible to autoxidation under extended storage conditions. The bis-allylic positions as found in linoleic (C18:2) and linolenic (C18:3) acids are even more prone to oxidation. Literature values for relative rates of oxidation are 1 for oleates, 41 for linoleates and 98 for linolenates [230].

Any attempt to correlate the properties of biodiesel with fatty acid profile is arduous due to complex nature of natural fats and oils. However, certain trends can be drawn, which are evident from the data presented in Table 5. Coconut oil, palm oil, animal fats etc. contain very high levels of saturated, low molecular weight fatty acids and relatively little unsaturated fatty acids. As a consequence, their esters possess a relatively high cloud point (CP), viscosity and calorific value. By contrast, safflower, rapeseed etc. have a very high proportion of unsaturated FA, with little saturated FA and lower CP.

4.2. Effect of feedstock on performance and emission

Several research works have been carried out on biodiesel combustion, performance and emissions. However, the effects of chemistry of biodiesel on diesel engine operation have been less investigated. Performance and emissions of biodiesel vary with different feedstock. The percentage variation of performance and emissions of different biodiesel with respect to diesel are shown in Figs. 5 and 6.

Satyanarayana et al. [206] compared COB (coconut oil biodiesel), POB (palm oil biodiesel) and ROB (rubber seed oil biodiesel) and showed that high viscosity along with low volatility cause incomplete combustion which resulted in higher CO emission and less brake thermal efficiency (28.04%), compared to POB (37.78%) and ROB (33%) at optimum load (4.1 kW). However, the HC emission was higher for POB. In contrast to the other biodiesels, ROB exhibited lower emission of NO_x at lower load due to increase in cetane number that reduced the ignition delay, ultimately reducing the combustion chamber temperature. While experimenting with honge oil methyl ester (HOME), sesame oil methyl ester (SOME) and jatropha oil methyl ester (JOME), Banapurmath et al. [231] have shown in his experiment that the lowest BTE was found for JOME as compared to other fuels. At 80% load, the BTE were 29, 29.51 and 30.4% for JOME, HOME and SOME, respectively. The reasons are low volatility, higher viscosity and density of the Jatropha oil. Emissions of smoke, HC and CO were highest for JOME due to poor atomisation resulted from heavier molecular structure and higher viscosity of JOME as compare to other fuels. As NO_x formation is strongly depends upon peak temperature, NO_x emission found lowest with JOME. Nitrogen oxides emission values were 970, 1000 and 990 ppm for JOME, SOME and HOME, respectively, compared to 1080 ppm with diesel operation at 80% load. In another investigation Rakopoulos et al. [139] have found similar values of BSFC and BTE for sunflower and cottonseed biodiesel due to similar value of calorific value and viscosity. However, emission of soot was more with cottonseed biodiesel due to presence of relatively higher

Table 5
Physicochemical properties of fuels.

Properties	Density at 15 °C (kg/m^3)	Viscosity (mm^2/s) at 40 °C	Iodine value	Cetane number	Calorific value (MJ/Kg)	Flash point (°C)	Cloud point (°C)	Pour point (°C)	Carbon	Hydrogen	Oxygen	Sulphur	Acid number mg KOH/g
Animal Fat [164]	920	45	na	40	39.770 (Lower)	na	na	na	73	12.3	12.5	0	na
Fish oil methyl ester [167], [186]	880	4.0	na	na	42.241	176	na	na	na	na	10.9	na	0.49
Lard methyl ester [186]	na	4.8	na	na	na	160	11	12	na	na	Na	na	0.44
Tallow methyl ester [163], [186], [209]	877 (at 17 °C)	5.0	58.8	58.8	39.858	150	11	9	76.77	12.88	11.47	0.18	0.33
Chicken fat methyl ester [186]	na	4.3	na	na	na	150	4.3	6	na	na	Na	na	na
Cotton seed oil ME [90], [91], [209]	850	6.0	105.7	52	41.680	200	−2	−4	77	12.5	10.49	< 0.005	0.09
Cotton seed oil [93], [210], [211]	876	34	na	38	39.47	234	1.7	−15	na	na	Na	na	na
Jatropha oil [80], [83], [197], [207]	910	38	105		39.584	235	9 ± 1	4 ± 1	76.11	10.52	11.06	0	0.929
Jatropha methyl ester [83], [84], [85], [203]	884	4.12	100	57	39.594	162	−4	−8	76.5	12	11.3	na	0.149
Jajoba oil [184]	920	52	81–88	55	39.862	186	16	−6	186	12.94	5.7	0.02	na
Karanja Methyl ester [88], [213], [214], [215]	885	9.6		48	36.12	187	−2	−6	na	na	Na	0.02	0.10
Linseed oil [57], [100], [103]	894.5	26	184	34.5	39.307	241	1.7	−15	na	na	Na	na	na
Linseed oil methyl ester [100]	890	4.3	184	48	40.759	161	na	−18	78.14	9.98	11.72	0.5	na
Coconut oil [48], [49], [198], [208]	920.6	28.05	6–11	na	38.68	228	na	na	na	na	Na	na	na
Coconut oil ME [47], [198], [203], [205]	874.8	4.07	30	59	38.1	178	25	22	72	12	16	3 ppm	0.29
Palm oil [131], [132], [207]	860	45	59	49	40.14	193	7.2	16	na	na	Na	0.004 (mg/kg)	na
Palm oil ME [134], [197], [199], [204]	864.42 (at 25 °C)	4.71	51	52	39.83	171	19	18	75.9	12.2	11.9	1.2 ppm	0.34
Olive oil [212]	925	32	na	39	37 (lower)	na	na	na	na	na	Na	na	na
Olive oil methyl ester [212]	0.888	4.70	na	61	32.71 (lower)	110	−2	−3	na	na	Na	na	na
Castor oil [178]	960	226.82	na	na	36.20	317	na	na	na	na	Na	na	1.642
Castor oil ME[178], [181]	913	10.50	na	na	46.22	149	na	na	72.10	12.29	Na	na	1.008
Waste oil ME [200], [155], [202], [209]	876.08	4.49	63.5	na	39.76	160	na	na	76.3	12.2	11.3	na	na
Sunflower oil [136], [137], [184]	910	62.1	126.3	36.7	39.6	232	−6.7	−12.2	77.15	11.93	10.86	0.001	na
Sunflower ME [138], [140], [203]	892	5.78	133	46.6	36.66 (lower)	157.6	0	−6	76.72	12.22	11.6	< 0.005	0.14
Peanut seed oil [201]	888	22.72	123.22	na	39.9	198.0	0.0	−6.0	70	na	Na	na	na
Peanut seed oil methyl ester [201]	848.5	4.42	67.45	53.59	40.1	166.0	0.0	−8.0	62.1	na	Na	na	na
Putranjiva oil [168]	na	37.62	na	31.3	39.582	48	na	−3	na	na	Na	na	na
Poon oil [172]	926 (40^{0}C)	49.7	78.1	na	39.65	158	6	−5	na	na	Na	na	0.36
clove stem oil [173]	1034	4.1	na	na	333.6	104	na	−57	na	na	Na	na	na
Balanites oil [174]	886	38.64	na	na	39.84	230	na	−3.5	na	na	Na	na	1.96
Balanites oil methyl ester [174]	860	3.98	na	na	39.65	75	na	−2.5	na	na	Na	na	0.34
Soybean BD [205], [209]	884.5	3.973	133.2	50.9	na	139	na	0	77.2	11.9	10.8	na	.16
Corn BD [205]	884	4.1769	na	60.9[a]	na	192	na	−1	na	na	Na	na	.17
Rapeseed BD [187], [205] [209]	882,8	4.34	97.4	52.9	na	107	−3.9	−8	na	na	Na	na	0.16
Rubber seed ME [205], [209]	na	4.98	97.4	na	37.78	164	5	−8	na	na	Na	na	0.11
Diesel [83], [202], [204], [178]	830	5.80	11	48	46.22 (gross)	47	−12	−17	86.4	12.88	Na	0.29	0.06

na—not available.
[a] Cetane index.

Table 6
European and U.S. specification for biodiesel [197,213].

Properties	U.S. (ASTM D6751–08)		Europe (EN 14214)	
	Limits	Method	Limits	Method
Water and sediments (vol% max)	0.05	D2709	0.05	EN12397[g]
Total contamination (mg/kg. max)			24	EN12662
Kinematic viscosity at 40 °C (mm^2/s)	1.9–6.0	D445	3.5–5.0	EN 3104/3105
Flash point closed cup (°C/min)	93	D93	101	EN3679
Cetane number (min)	47	D613	51	EN 5165
Cloud point (°C)	Report	D2500		EN
Sulfated ash (wt% max)	0.020	D874	0.020	EN 3987
Acid no. (mg KOH/g. max)	0.05	D664	0.05	En 14104
Oxidation stability (h at110 °C min)	3.0	EN14112	6.0	EN14112
Iodine value ($g/I_2/100$ g max)			120	EN 14111
Density (kg/m^3)			860–900	EN 3675
Free glycerin (wt%max)	0.02	D6584	0.02	EN 14105/14106
Total glycerin (wt%max)	0.24	D6584	0.25	EN 14105
Mono glyceride (wt%max)			0.80	EN 14105
Glyceride (wt%max)			0.20	EN 14105
Glyceride (wt%max)			0.20	EN 14105

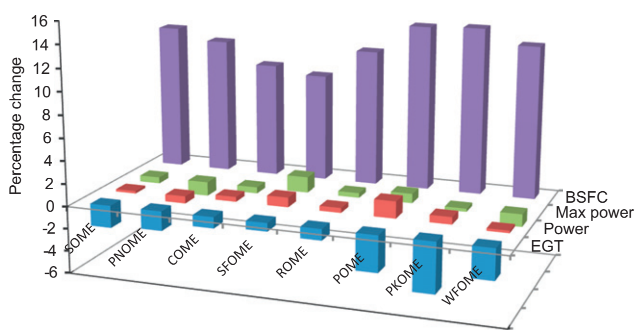


Fig. 5. Variation in performance for different biodiesel [192].

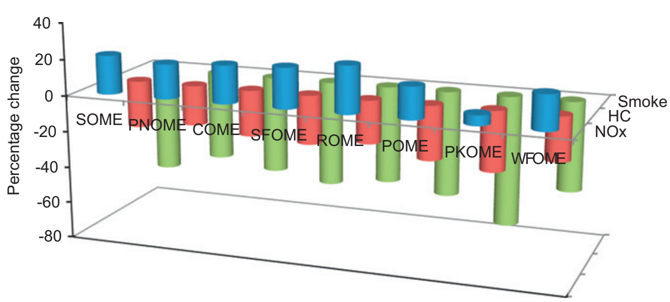


Fig. 6. Variation in exhaust emissions for different biodiesel [192].

content of palmitic acid and lower content of linoleic acids, in cottonseed compared to those of the sunflower. It is believed that formation of soot particles starts with polymerization of species containing a double carbon bond. This was also the reason for lower emission of CO with cottonseed biodiesel as compared to sunflower biodiesel. However, the cottonseed biodiesel blends tend to produce a little higher exhaust NO_x and HC values than the corresponding one for the sunflower case. In another experiment [192], the variation of performance and emissions of different biodiesels produced from soybean oil (SOME), peanut oil (POME), corn oil (COME), sunflower oil (SFOME), rapeseed oil (ROME), palm oil (POME), palm kernel oil (PKOME), and waste fried oil (WFOME) with respect to diesel were tested in a single cylinder, 4-stroke, water-cooled, DI diesel engine. PKOME and POME, due to lower calorific value among tested fuels, exhibited significantly higher BSFC. Complete combustion of POME and PKOME can be achieved due to shorter carbon chains, mainly C12 and C16, which resulted in lower smoke emission. Furthermore, NO_x emission was lowest for PKOME and POME among all esters due to the fact that fuel with more saturated carbon bonds is more useful in reducing the NO_x emissions and PKOME and POME consist of more saturated carbon bonds around 50 and 80%, respectively. All biodiesels yielded the same engine power as diesel at full load condition as well as at average load condition for various engine speeds. The authors suggested that it was due to the higher BSFC, increased oxygen content, and higher combustion rate of the esters. Lower EGT was reported by using PKOME and POME in diesel engine as the lower calorific value of these esters resulted in lower total heat release.

Puhan et al. [191] conducted experiments with coconut (COTME), Jatropha (JOME) and linseed (LOME) biodiesel to evaluate the effect of biodiesel molecular weight, structure (*cis* and *trans*), and number of double bonds on performance and emission of the diesel engine. The test results revealed that LOME showed a marginal increase in BSEC compared to other biodiesels at higher load owing to the advancement in dynamic injection time due to higher density of LOME, as shown in Table 5. The BTE was lowest at full load in the case of LOME due to the presence of tri-unsaturated linolenic acid, which polymerises at high temperature in the presence of oxygen, and leads to extended after burning combustion. Also, reduced spray droplet contributed towards lower BTE. While at lower loads, JOME exhibits higher thermal efficiency. As expected, polyunsaturated fatty acids in LOME, increases ignition delay and leads to shorter premixed combustion and an increase in after-burning combustion that resulted in highest EGT of the LOME compared to other biodiesels. LOME emitted higher CO emission due to low oxidants concentration and shorter reaction time. Advancement in injection timing for LOME resulted in higher emission of HC and NO_x as compared to other biodiesels.

Schönborn et al. [188] has experimentally investigated pure individual fatty acid alcohol ester molecules of different structure, as well as several mixtures of such molecules under three constant experimental conditions namely injection timing, ignition timing and ignition delay. The investigation shows that a longer fatty acid chain length resulted in a shorter ignition delay and lower NO_x emission. For constant ignition timing, shorter chained molecules and unsaturated molecules produce higher NO_x emissions. It was also reported that with increasing double bond, ignition delay increases and the longest ignition delay and

highest NO_x emission were experienced by the polyunsaturated methyl ester (C18:2). When the effect of ignition delay was neutralised higher concentrations of NO_x emission was reported with unsaturated molecules. Owing to the high viscosity, longest molecule (behenic acid methyl ester) emitted greater amount of particulate mass. The emission of particulate matter clearly increases with increasing number of double bonds within the fatty acid moiety of the ester molecules. Unsaturated molecules produce more ethene and ethyne during thermal decomposition and have a higher chemical propensity to form soot. The results were validated by experimenting with different biodiesel. For all cases RME produced significantly higher NO_x emissions and the highest amount of particulate mass amongst the biodiesel fuels. In another experiment [232], the unsaturated fuel, methyl crotonate was compared to the saturated methyl butanoate in a premixed and non-premixed combustion experiments. The results suggested that an unsaturated FAME due to formation of soot precursors such as C_2H_2, 1-C_3H_4, 1-C_4H_8, and 1,3-C_4H_6 would have a greater tendency to soot formation than a saturated FAME. While Anderson et al. [233] concluded that vegetable oils with high percentages of fully saturated fatty acids (e.g., palmitic and stearic acid) have the potential to produce lower NO_x emissions but high viscosity and poorer cold flow properties. On the other hand vegetable oils with high in polyunsaturated fatty acids (e.g., linoleic and linolenic acid) are less viscous, but contribute to cylinder buildup and higher NO_x emissions.

4.3. *Effect of biodiesel on engine performance and emission*

In this work, performance and emissions of different biodiesel reported by different authors have been studied.

4.3.1. *Performance*

4.3.1.1. Power. A group of authors agree that the engine power decreased with the utilisation of biodiesel [90,92,141,163]. The reasons are—less calorific value of biodiesel and in efficient combustion of biodiesel [92,163,234]. Some authors [138,165] also reported some power recovery and it is attributed to the higher density, higher bulk modulus and higher viscosity of biodiesel. High density results in injection of increased mass of fuel, while high viscosity reduces the leakage [165]. However, the higher mass fuel flow for the methyl ester is not sufficient to compensate for the approximately 12.8% lower heating value compared to diesel fuel [138].

It was also reported by some authors that there was no significant difference in engine power between biodiesel and diesel [192,235]. The explanation is that engine delivers fuel on volumetric basis and biodiesel density is higher than that of diesel, which supplies more biodiesel to compensate the lower heating value [122]. Higher viscosity of biodiesel leads to larger spray droplet which enhances fuel spray penetration due to higher momentum, thus improving air–fuel mixing [149]. In addition, in-built oxygen of biodiesel also benefits the combustion process [236–238]. Therefore, the higher BSFC of biodiesel and improved combustion are the reasons for increase in the engine power.

Finally, increase in power or torque of engine was also reported in some literature for biodiesel [178]. This increase is attributed to the higher oxygen content, the higher biodiesel consumption, an advance of injection timing and a shorter ignition delay time. [239].

In general more saturated biodiesels have higher calorific value as shown in Table 5, and are expected to produce more power than less saturated biodiesel. Moreover, higher viscosity reduces leakage and high cetane number reduces the ignition delay time.

4.3.1.2. Brake specific fuel consumption. Most of the authors reported an increase in fuel consumption in case of biodiesel compared to diesel [83,91,163,167,178]. This increase is due to combined effects of the higher fuel density, viscosity and low heating value of biodiesel. As the BSFC was calculated on weight basis, obviously higher densities resulted in higher values for BSFC as higher mass injection for the same volume at the same injection pressure. Also, the higher density of biodiesel has led to more discharge of fuel for the same displacement of the plunger in the fuel injection pump, thereby increasing the specific fuel consumption. In addition, the lower heating value of biodiesel requires that a larger amount of fuel to be injected into the combustion chamber to produce the same power [83,91].

Some experimental results revealed no significant difference in the fuel consumption between biodiesel and diesel [240]. In contrast to all above view, some authors [86,241–243] reported decrease in BSFC for biodiesel in comparison to diesel. Among different biodiesels, biodiesel with particularly low volumetric calorific values and shorter carbon-chains, resulted in their BSFC being significantly higher than that of the other biodiesels [192].

4.3.1.3. Brake thermal efficiency. The BTE obtained from biodiesel was found to be less than that of diesel [83,85,167]. The reduction of brake thermal efficiency with biodiesel mixtures was attributed to poor spray characteristics, poor air fuel mixing, higher viscosity, higher volatility and lower calorific value [91]. The other reason given as smaller ignition delay of biodiesel resulted in initiation of combustion much before TDC causing increases in the compression work as well as heat loss and leads to reduction in the efficiency of the engine [84].

A few other authors [126] found no significant difference between biodiesel and diesel as engine converts the chemical energy of the fuel to mechanical energy with the same efficiency. However, some literatures [140] reported that BTE increased for biodiesel compared to diesel.

4.3.2. *Emission*

4.3.2.1. CO emissions. For the biodiesel, the CO emissions were less than for the diesel fuel [83,126,163,244]. Canakci [126], Oner and Altun [163] and Nabi et al. [244] found 18.4, 14.5 and 4% reductions in CO emissions, respectively, when the engine was fuelled with B100. This may be due to oxygen content of biodiesel and its blends. In addition, lower C/H ratio of biodiesel compare to diesel also reduces CO emission. However, the amount of decrease in CO emissions does not depend on biodiesel percentage in fuels. Biodiesel contain oxygen in their molecule that resulted in complete combustion of the fuel and supplied the necessary oxygen to convert CO to CO_2 [91].

4.3.2.2. NO_x emissions. No unanimity regarding emission of NO_x was found in the literature. Some of the literature reported less NO_x emission with the utilisation of biodiesel [212,240]. Oner et al. [212] reported 38.4% reduction, while Sahoo et al.[240] reported 4% reduction. The explanations given are higher cetane number and lower flash point of biodiesel as compared to diesel. Increasing cetane number reduces the size of the premixed combustion by reducing the ignition delay and hence lower NO_x formation rate since the combustion pressure rises more slowly giving more time for cooling through heat transfer and dilution and leading to lower localized gas temperatures [212]. Absence of aromatic and polyaromatic hydrocarbons in biodiesel lowers the flame temperature, ergo less NO_x emission. Also, shorter ignition delay due to higher cetane number would allow less time for the air/fuel mixing before the premixed burning phase. Consequently,

a weaker mixture would be generated and burnt during the premixed phase resulting in relatively reduced NO_x formation [245]. Saturation in the fatty compounds causes decrease in NO_x emissions [246]. Wyatt et al. [186] have reported that all the animal fat biodiesels, including beef tallow, lard and chicken, had lower NO_x levels compared to the soy oil based biodiesel due to higher saturation level and cetane number.

Increases in NO_x formation were also reported [154]. The major causes for biodiesel's increased NO_x emissions include advanced start of combustion and faster burn rate, decreased radiation heat transfer, different adiabatic flame temperature and system response issues. Inbuilt oxygen of bidiesel is also responsible for extra NO_x emission. Approximately 10% increase in NO_x emission was realized with 30% biodiesel mixtures [84]. Higher bulk modulus and higher cetane number of biodiesel significantly shortens injection delay and results in faster ignition than diesel fuel [247]. Furthermore, the higher adiabatic flame temperature due to the more double-bonded molecules of biodiesel fuel also increases NO_x emission [124]. It is also reported that higher amount of biodiesel injected due to high density and increased injection pressure at the same injection setting causes combustion to take place over a shorter period of time and results in lower cooling by heat transfer and dilution, and higher NO_x emission [83]. Further, older engines with lower injection pressure are generally very sensitive to CN in comparison to modern engine—with increased CN, NO_x emissions reduces significantly. NO_x emissions reportedly increase with decreasing saturation and chain length, which can also lead to a connection with the CNs of these compounds [248].

4.3.2.3. PM and smoke. PM (particulate matter) is composed mainly of three components: DS (dry soot), sulfate and SOF (soluble organic fraction) [249]. The literature review [154,250] shows that PM emissions were generally reduced with the use of biodiesel as compare to diesel; due to the oxygen contained in the biodiesel molecules, the low levels of sulphur content and higher cetane number. Particulate matters were formed in the locally rich regions of the heterogeneous mixture of fuel and air during combustion in the combustion chamber. Further mixing of air and fuel resulted in burning of particulate at the boundary of diffusive flame due to the high temperature and available oxygen at the region. The increase of oxygen content in the biodiesel which contributes to a complete fuel oxidation even in locally rich zones, led to a significant decrease in PM and smoke [251]. Higher cetane number of biodiesel compared to diesel resulted in shorter ignition delay and longer combustion duration, and hence low particulate emissions [91]. Diesel contains sulphur which results in sulphates that are absorbed on soot particles and increase the PM emitted from diesel engines. As biodiesel is free from sulphur, and it has an advantage over diesel [212]. In addition, utilisation of biodiesel substantially reduced the larger size particulates, which strongly contributed to the volume and weight of particulates. At the same time, biodiesel produced lower concentrations of particulates [124]. Low C/H ratio also lowered the smoke emission [252]. If the applied fuel is partially oxygenated, locally over-rich regions can be reduced and primary smoke formation can be limited [91]. Finally, as the requirement of the stoichiometric air for biodiesel is lower [19,21], it reduces the formation of fuel-rich regions in the heterogeneous mixture and PM emission [253]. However, the soluble organic fraction (SOF) of the PM was significantly higher with the biodiesel [246].

4.3.2.4. HC emission. Many previous studies have reported significant reduction in HC emission, however the reduction amount vary in the reported data [116,173,254]. Kalligeros et al. [212] reported that the addition of methyl esters contributed to a faster evaporation and more stable combustion, and hence, a decrease in HC in comparison to diesel. The oxygen contains and higher cetane number of biodiesel along with advanced injection and combustion timing reduces HC emission for biodiesel significantly [255]. As discussed, oxygen provides cleaner combustion while advance in injection provides more time for oxidation of HC. Further, HC emission reported to be function of load. At higher loads, HC emission increases due to higher fumigation rate and non-availability of oxygen relative to diesel [172].

4.3.2.5. CO_2 emission. CO_2 emissions of biodiesel are higher than that of diesel fuel [83,173,256]. Presences of oxygen in biodiesel and relatively lower content of carbon in biodiesel for the same volume of fuel consumed are cited as the reasons for higher emission of CO_2 [83].

However, some researcher reported lower CO_2 emissions for biodiesel than diesel [83,257]. The explanations given are that the high viscosity of biodiesel reduces cone angle which leads to reduction of amount of air entrainment in the spray resulting in hindrance in complete combustion [257,258].

5. Conclusion

The choice of feedstock for biodiesel often depends upon domestic source. Being renewable and sustainable source of fuel, biodiesel will play dominating role in transport sector in the near future. The properties of biodiesel depend on the fatty acid compositions of the parent oil or fat, which are highly influenced by the nature of the feedstock. The properties of the biodiesel are similar to the diesel. However, the variation in the properties of the biodiesel causes variation in the nature of the performance and emission of the diesel engine. In-depth understanding of the relation exhibited between nature of the feedstock of biodiesel and performance and emission may pave way for a more detailed exploration of biodiesel in diesel engine. Furthermore, the effect of different types of engine is also an influential factor to be considered while evaluating the performance and emission of engine. Beside these factors, other factors, such as, difference in used diesel, the different measurement techniques or instruments etc., are also instrumental in providing fluctuating results. Based on the above discussion, a concrete relationship is hard to establish. However, following conclusions can be drawn.

(1) Compositions of oil determine the properties of biodiesel. More saturated esters have higher cetane number, lower iodine number and lower density than less saturated esters. The density of shorter chain length saturated esters is greater than longer chain saturated esters. Unsaturated biodiesels are better in terms of cold flow properties and viscosity; however, they display poor oxidation stability.
(2) Biodiesel produced from more saturated feedstock tends to produce less NO_x emission and resistive to the oxidation but exhibit poor atomisation due to high viscosity. Shorter chain length saturated esters produces more NO_x emission than longer chain length. Slightly compromising on the performance, biodiesel produced from saturated feedstock such as animal fat may provide a better solution to reduce NO_x emission. The most highly unsaturated fuels (canola and soy) produce the highest NO_x emissions.
(3) Different trends in performance and emissions are reported in the literature reviewed. Decrease in power and brake

thermal efficiency with increase in fuel consumption is usually reported. In most cases, hydrocarbons, PM and CO emissions are found to significantly decrease with biodiesel. No accredited result is reported for NO_x emission.

(4) In general, if non-edible oils are used as biodiesel, food versus fuel conflict does not arise. In the same manner, algae can also become natural choice for feedstock.

(5) The reasons for such fluctuating results must be analysed for further improvement in utilisation of biodiesel for commercial purpose. Future research should be focused to genetically improve the feedstock of biodiesel so that a similar composition of fatty acid can be achieved. Further improvement in the specification of biodiesel is required.

References

[1] Mirza UK, Ahmad N, Majeed T. An overview of biomass energy utilization in Pakistan. Renewable and Sustainable Energy Reviews 2007;12:1988–96.
[2] Chang J, Leung DYC, Wu CZ, Yuan ZH. A review on the energy production, consumption, and prospect of renewable energy in China. Renewable and Sustainable Energy Reviews 2003;7:453–68.
[3] Correa SM, Arbilla G. Carbonyl emissions in diesel and biodiesel exhaust. Atmospheric Environment 2008;42:769–75.
[4] Agnes SF, et al. Renewable energy generation by full-scale biomass gasification system using agricultural and forestal residues. Practice Periodical of Hazardous, Toxic, Waste Management 2007;11:177–83.
[5] Senthikumar G, Gunasekaran P. Bioethnol production from cellulosic substance: engineered bacteria and process integration challenge. Journal of Scientific and Industrial Research 2005;64:845–53.
[6] Demirbas A. Biodiesel production from vegetable oil by supercritical methanol. Journal of Scientific and Industrial Research 2005;64:858–65.
[7] Raja A, Sarvanan B, Sitharthaseelan J, Sudhkar S, Sarvanan GS. Fumigation of methanol in diesel engine through recovering waste heat from exhaust gas with fuel additives. Journal of the Institution of Engineers (India) 2003;83:153–7.
[8] Sheehan J, Combreco V, Duffield J, Garboski M, Shapouri H. An overview of biodiesel and petroleum diesel life cycle. A report by US department of Agriculture and Energy, National Renewable Energy laboratory, Golden, CO, US; May 1998.
[9] Ramadhas AS, Jayaraj S, Muraleedharan C. Theoretical modeling and experimental studies on biodiesel-fueled engine. Renewable Energy 2006;31:1813–26.
[10] Giibitz GM, Mittelbach M, Trabi M. Exploitation of the tropical oil seed plant *Jatropha curcas* L. Bioresource Technology 1999;67:73–82.
[11] Sethi VP, Salaria KS. Exhaust analysis and performance of a single cylinder engine run on dual fuels. Journal of the Institution of Engineers (India) 2004;85:1–7.
[12] Huang Y, Wu J. Analysis of biodiesel promotion in Taiwan. Renewable and Sustainable Energy Reviews 2008;12:2472–83.
[13] Kondilia EM, Kaldellis JK. Biofuel implementation in East Europe: current status and future prospects. Renewable and Sustainable Energy Reviews 2007;11:2137–51.
[14] Marchetti JM, Miguel VU, Errazu AF. Possible methods for biodiesel production. Renewable and Sustainable Energy Reviews 2007;11:1300–11.
[15] Agarwal AK, Rajamanoharan K. Experimental investigations of performance and emissions of Karanja oil and its blends in a single cylinder agricultural diesel engine. Applied Energy 2009;86:106–12.
[16] Ramadhas AS, Jayaraj S, Muraleedharan C. Use of vegetable oils as I.C. engine fuels—a review. Renewable Energy 2004;29:727–42.
[17] Meher LC, Sagar DV, Naik SN. Technical aspects of biodiesel production by transesterification—a review. Renewable and Sustainable Energy Reviews 2006;10(248):68.
[18] Vasudevan P, Sharma S, Kumar A. Liquid fuel from Biomass: an overview. Journal of Scientific and Industrial Research 2005;64:822–31.
[19] Zejewski M, Goettler H, Pratt GL Influence of vegetable oil based alternative fuels on residue deposits and components wear in a diesel engine. SAE paper 860302; 1986.
[20] Pryde EH. Vegetable oils as diesel fuels: overview. Journal of the American Oil Chemists Society 1983;60(8):1557–8.
[21] Kouzu M, Hidaka J. Transesterification of vegetable oil into biodiesel catalyzed by CaO: a review. Fuel 2012;93:1–12.
[22] Shahid EM, Jamal Y. Production of biodiesel: a technical review. Renewable and Sustainable Energy Reviews 2011;15(9):4732–45.
[23] Viola E, et al. Biodiesel from fried vegetable oils via transesterification by heterogeneous catalysis. Catalysis Today 2012;179(1):185–90.
[24] Schumacher LG, Gerpen JV, Adams B. Biodiesel fuels. ENC Energy 2004;1: 151–62.
[25] Amigun B, Sigamoney R, Blottnitz H. Commercialisation of biofuel industry in Africa: a review. Renewable and Sustainable Energy Reviews 2008;12:690–711.
[26] Kalayasiri P, Jeyashoke N, Krisnangkura K. Survey of seed oils for use as diesel fuels. Journal of the American Oil Chemists Society 1996;73(4): 471–4.
[27] Lim S, Teong LK. Recent trends, opportunities and challenges of biodiesel in Malaysia: an overview. Renewable and Sustainable Energy Reviews 2010;14:938–54.
[28] Chisti Y. Biodiesel from microalgae. Biotechnology Advances 2007;25: 294–306.
[29] Haas MJ, Scott KM, Alleman TL, McCormick RL. Engine performance of biodiesel fuel prepared from soybean soapstock: a high quality renewable fuel produced from a waste feedstock. Energy and Fuels 2001;15:1207–12.
[30] Ramadhas AS, Jayaraj S, Muraleedharan C. Biodiesel production from high FFA rubber seed oil. Fuel 2005;84:335–40.
[31] Johanes BH, Shizuko H. Biodiesel production from crude *Jatropha curcas* L. seed oil with a high content of free fatty acids. Bioresource Technology 2008;99(6):1716–21.
[32] Knothe G, Steidley KR. A comparison of used cooking oils: a very heterogeneous feedstock for biodiesel. Bioresource Technology 2009;100:5796–801.
[33] Monteiro MR, Ambrozin ARP, Lião LM, Ferreira AG. Critical review on analytical methods for biodiesel characterization. Talanta 2008;77: 593–605.
[34] Sharma YC, Singh B. Development of biodiesel: current scenario. Renewable and Sustainable Energy Reviews 2009;13:1646–51.
[35] Hanna MA, Iscon L, Campbell J. Biodiesel: current perspective and future. Journal of Scientific and Industrial Research 2005;64:854–7.
[36] U.S. Energy Information Administration, International Energy Statistics, Biofuels Production. Available at 〈http://tonto.eia.gov〉. last accessed 05.04.12.
[37] Galbe M, Liden G, Zacchi G. Production of ethanol from biomass—research in Sweden. Journal of Scientific and Industrial Research 2005;64:905–19.
[38] His S. Biofuels in Europe. Journal of Scientific and Industrial Research 2005;64:931–5.
[39] Monyem A, Gerpen JHV. The effect of biodiesel oxidation on engine performance and emissions. Biomass and Bioenergy 2001;20:317–25.
[40] Kallivroussis L, Natsis A, Papadakis G. The energy balance of sunflower production for biodiesel in Greece. Biosystems Engineering 2002;81: 347–54.
[41] Panoutsou C, Namatov I, Lychnaras V, Nikolaou A. Biodiesel options in Greece. Biomass and Bioenergy 2008;32:473–81.
[42] Bomb C, McCormick K, Deurwaarder E, Kaberger T. Biofuels for transport in Europe: lessons from Germany and the UK. Energy Policy 2007;35: 2256–67.
[43] Hammond GP, Kallu S, McManus MC. Development of biofuels for the UK automotive market. Applied Energy 2008;85:506–15.
[44] European Biodiesel Board. available on 〈www.ebb-eu.org〉 (last accessed 15.02.12).
[45] Dorado MP, Cruz F, Palomar JM, Lopez FJ. An approach to the economics of two vegetable oil-based biofuels in Spain. Renewable Energy 2006;31: 1231–7.
[46] Katinas V, Markevicius A, Kavaliauskas A. Current status and prospects of biomass resources for energy production in Lithuania. Renewable Energy 2007;32:884–94.
[47] Hoekman SK. Biofuels in the U.S.—challenges and opportunities. Renewable Energy 2009;34:14–22.
[48] Farzaneh M, Zietsman J, Perkinson D, Spillane D. The impact of biodiesel on emissions from school buses. Transportation Land Use Planning and Air Quality Congress 2007. 2008;395-407.
[49] Foglia TA, Jones KC, Phillips JG. Determination of biodiesel and triacylglycerols in diesel fuel by LC. Chromatographia 2005;62:115–9.
[50] Mandal R, Mithra P. The Indian biofuel program: the national mission on biodiesel. Biofuels towards a greener and secure future, editor P P Bhojvaid, TERI publication.
[51] Ramos LP, Wilhelm HM. Current status of biodiesel development in Brazil. Applied Biochemistry and Biotechnology 2005;123:807–19.
[52] Soccol CR, et al. Brazilian biofuel program: a review. Journal of Scientific and Industrial Research 2005;64 897-4.
[53] Schaffel SB, Rovere ELL. The quest for eco-social efficiency in biofuels production in Brazil. Journal of Cleaner Production 2010;18:1663–70.
[54] Koizumi T. The Japanese biofuel program—developments and perspectives. J Clean Prod doi:10.1016/j.jclepro.2011.04.022.
[55] Eijck JV, Romijn H. Prospects for jatropha biofuels in Tanzania: an analysis with strategic niche management. Energy Policy 2008;36:311–25.
[56] Economic Survey 2010–2011 available at 〈http://indiabudget.nic.in〉, (last accessed 30.01.2012).
[57] US energy Administration. 〈www.eia.gov〉 (last accessed 25.01.2012).
[58] Ministry of external affairs, Govt. of India, available at 〈http://meaindia.nic.in/〉 (last accessed 5.08.2011).
[59] Transport and communication, 9th Five Year Plan (vol-2), Planning commission of India, Govt. of India, 〈http://planningcommission.gov〉.in (last accessed 12.09.11).
[60] Ministry of Commerce and Industry, Government of India, available at 〈http://commerce.nic.in/pressrel.html〉 (last accessed 10.03.12).
[61] Ministry of Consumer Affairs, Food & Public Distribution. 〈www.fcamin.nic〉.in (last accessed 10.04.12).

[62] Puhan S, Vedraman N, Rambrahaman BV, Nagranjan G. Mahua (*Madhuca indica*) seed oil: a source of renewable energy in India. Journal of Scientific and Industrial Research 2005;64:890–6.
[63] Report of the committee on development on biofuel, planning commission, Govt. Of India, 〈http://planningcommission.nic.in/reports/genrep/cmtt_bio.pdf〉 (last accessed 10.09.11).
[64] Ministry of Rural Development, Govt. of India, 〈www.rural.nic.in〉 (last accessed 06.09.11).
[65] Srivastva L. Biofuel in the India prospective, Section I, Biodiesel towards a greener and secure energy future. TERI publication, editor P P Bhojvaid, pp. 3–11.
[66] Azam MM, Waris A, Nahar NM. Prospects and potential of fatty acid methyl esters of some non-traditional seed oils for use as biodiesel in India. Biomass and Bioenergy 2005;29:293–302.
[67] Annual Report, 2004–2005, Ministry of Non-conventional Energy Sources, Govt. of India, 〈www.mnes.nic.in〉 (last accessed 12.11.11).
[68] Bozbas K. Biodiesel as an alternative motor fuel: production and policies in the European Union. Renewable and Sustainable Energy Reviews 2008;12: 542–52.
[69] Phalakornkule C, Petiruksakul A, Puthavithi W. Biodiesel production in a small community: case study in Thailand. Resources, Conservation and Recycling 2009;53:129–35.
[70] Jayed MH, Masjuki HH, Kalam MA, Mahlia TMI, Husnawan M, Liaquat AM. Prospects of dedicated biodiesel engine vehicles in Malaysia and Indonesia. Renewable and Sustainable Energy Reviews 2011;15:220–35.
[71] Grau B, Bernat E, Antoni R, Jordi-Roger R, Rita P. Small-scale production of straight vegetable oil from rapeseed and its use as biofuel in the Spanish territory.
[72] Biodfuels Annual, India 2012. GAIN Report Number: IN208. Available online 〈http://gain.fas.usda.gov/Recent%20GAIN%20Publications/Biofuels%20Annual_New%20Delhi_India_6-20-2012〉.pdf.
[73] Poitrat E. The potential of liquid biofuels In France. Renewable Energy 1999;16:1084–9.
[74] Demirbas A. Biodiesel fuels from vegetable oils via catalytic and non-catalytic supercritical alcohol transesterifications and other methods: a survey. Energy Conversion and Management 2003;44:2093–109.
[75] Koh MY, Ghazi TIM. A review of biodiesel production from *Jatropha curcas* L. oil. Renewable and Sustainable Energy Reviews 2011;15(5):2240–51.
[76] Vyas DK, Singh RN. Feasibility study of jatropha seed husk as an open core gasifier feedstock. Renewable Energy 2007;32:512–7.
[77] Kumar N, Sharma PB. *Jatropha curcus*-A sustainable source for production of biodiesel. Journal of Scientific and Industrial Research 2005;64:883–9.
[78] Shah S, Sharma A, Gupta MN. Extraction of oil from *Jatropha curcas* L. seed kernels by combination of ultrasonication and aqueous enzymatic oil extraction. Bioresource Technology 2005;96:121–3.
[79] Shah S, Sharma A, Gupta MN. Extraction of oil from *Jatropha curcas* L. seed kernels by enzyme assisted three phase partitioning. Industrial Crops and Products 2004;20:275–9.
[80] Agarwal D, Agarwal AK. Performance and emissions characteristics of jatropha oil (preheated and blends) in a direct injection compression ignition engine. Applied Thermal Engineering 2007;27:2314–23.
[81] Forson FK, Oduro EK, Hammond-Donkoh E. Performance of jatropha oil blends in a diesel engine. Renewable Energy 2004;29:1135–45.
[82] Reddy JN, Ramesh A. Parametric studies for improving the performance of a jatropha oil-fuelled compression ignition engine. Renewable Energy 2006;31:1994–2016.
[83] Chauhan BS, Kumar N, Cho HM. A study on the performance and emission of a diesel engine fueled with jatropha biodiesel oil and its blends. Energy 2012;37(1):616–22.
[84] Rao GLN, Prasad BD, Sampath S, Rajagopal K. Combustion analysis of diesel engine fueled with jatropha oil methyl ester—diesel blends. International Journal of Green Energy 2007;4:645–58.
[85] Jindal S, Nandwana BP, Rathore NS, Vashistha V. Experimental investigation of the effect of compression ratio and injection pressure in a direct injection diesel engine running on jatropha methyl ester. Applied Thermal Engineering 2010;30:442–8.
[86] Mahanta P, Mishra SC, Kushwah YS. An experimental study of *Pongamia pinnata* L oil as a diesel substitute. Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy 2006;220(7):803–8.
[87] Sureshkumar K, Velraj R, Ganesan R. Performance and exhaust emission characteristics of a CI engine fuelled with *Pongamia pinnata* methyl ester (PPME) and its blends with diesel. Renewable Energy 2008;33:2294–302.
[88] Srivastava PK, Verma M. Methyl ester of karanja oil as an alternative renewable source energy. Fuel 2008;87:1673–7.
[89] Baiju B, Naik MK, Das LM. A comparative evaluation of compression ignition engine characteristics using methyl and ethyl esters of karanja oil. Renewable Energy 2009;34:1616–21.
[90] Karabektas M, Ergen G, Hosoz M. The effects of preheated cottonseed oil methyl ester on the performance and exhaust emissions of a diesel engine. Applied Thermal Engineering 2008;28:2136–43.
[91] Nabi MN, Rahman MM, Akhter MS. Biodiesel from cotton seed oil and its effect on engine performance and exhaust emissions. Applied Thermal Engineering 2009;29:2265–70.
[92] Aydin HS, Bayindir H. Performance and emission analysis of cottonseed oil methyl ester in a diesel engine. Renewable Energy 2010;35:588–92.
[93] He Y, Bao YD. Study on cottonseed oil as a partial substitute for diesel oil in fuel for single-cylinder diesel engine. Renewable Energy 2005;30:805–13.
[94] Aigbodion AI, Pillai CKS. Preparation, analysis and applications of rubber seed oil and its derivatives in surface coatings. Progress in Organic Coatings 2000;38(108):187–92.
[95] Zhu Y, Xu J, Mortimer PE. The influence of seed and oil storage on the acid levels of rubber seed oil, derived from *Hevea brasiliensis* grown in Xishuangbanna, China. Energy 2011;36:5403–8.
[96] Ramadhas AS, Jayaraj S, Muraleedharan C. Characterization and effect of using rubber seed oil as fuel in the compression ignition engines. Renewable Energy 2005;30 795–03.
[97] Ramadhas AS, Muraleedharan C, Jayaraj S. Performance and emission evaluation of a diesel engine fueled with methyl esters of rubber seed oil. Renewable Energy 2005;30:1789–800.
[98] Ramadhas AS, Jayaraj S, Muraleedharan C. Theoretical modeling and experimental studies on biodiesel-fueled engine. Renewable Energy 2006;31:1813–26.
[99] Agarwal AK, Das LM. Biodiesel development and characterization for use as a fuel in compression ignition engines. Transactions of ASME Journal of Engineering for Gas Turbines and Power 2001;123:440–7.
[100] Puhan S, Jegan R, Balasubbramanian K, Nagarajan G. Effect of injection pressure on performance, emission and combustion characteristics of high linolenic linseed oil methyl ester in a DI diesel engine. Renewable Energy 2009;34:1227–33.
[101] Agarwal AK, Bijwe J, Das LM. Wear assessment in a biodiesel fueled compression ignition engine. Transactions of ASME Journal of Engineering for Gas Turbines and Power 2003;125:820–6.
[102] Agarwal AK, Bijwe J, Das LM. Effect of biodiesel utilization of wear of vital parts in compression ignition engine. Transaction of ASME Journal of Engineering for Gas Turbines and Power 2003;125:604–11.
[103] Raheman H, Ghadge SV. Performance of compression ignition engine with mahua (*Madhuca indica*) biodiesel. Fuel 2007;86:2568–73.
[104] Agarwal D, Kumar L, Agarwal AK. Performance evaluation of a vegetable oil fuelled compression ignition engine. Renewable Energy 2008;33(6):1147–56.
[105] Kapilan N, Reddy RP. Evaluation of methyl esters of mahua oil (*Madhuca indica*) as diesel fuel. Journal of the American Oil Chemists Society 2008;85:185–8.
[106] Godiganur S, Murthy CHS, Reddy RP. 6BTA 5.9 G2-1 Cummins engine performance and emission tests using methyl ester mahua (*Madhuca indica*) oil/diesel blends. Renewable Energy 2009;34:2172–7.
[107] Puhan S, Vedaraman N, Sankaranarayanan G. Ram BVB. Performance and emission study of mahua oil (*madhuca indica* oil) ethyl ester in a four stroke natural aspirated direct injection diesel engine. Renewable Energy 2005;30: 1269–78.
[108] Puhan S, Vedaraman N, Rambrahamam BV, Nagrajan G. Mahua (*Maduca indica*) seed oil: a source of renewable energy in India. Journal of Scientific and Industrial Research 2005;64:890–6.
[109] Demirbas MF. Biofuels from algae for sustainable development. Applied Energy 2011;88:3473–80.
[110] Najafi G, Ghobadian B, Yusaf TF. Algae as a sustainable energy source for biofuel production in Iran: a case study. Renewable and Sustainable Energy Reviews 2011;15:3870–6.
[111] Demirbas A, Demirbas MF. Importance of algae oil as a source of biodiesel. Energy Conservation Management 2011;52:163–70.
[112] Haik Y, Selim MYE, Abdulrehman T. Combustion of algae oil methyl ester in an indirect injection diesel engine. Energy 2011;36:1827–35.
[113] Jayadas NH, Nair KP. Coconut oil as base oil for industrial lubricants—evaluation and modification of thermal, oxidative and low temperature properties. Tribology International 2006;39:873–8.
[114] Majuski HH, Kalam MA, Maleeue MA, Kubo A, Nonaka T. Performance emission and wear characteristics of an indirect injection diesel engine using coconut oil blended diesel. Journal of Automobile Engineering 2001;215:393–404.
[115] Raffiq HM, Ahmed KMB. Emission control for a direct diesel injection CI engine using preheated coconut oil blended diesel. Journal of the Institution of Engineers (India) 2005;86:149–52.
[116] Kalam MA, Husnawan M, Masjuki HH. Exhaust emission and combustion evaluation of coconut oil-powered indirect injection diesel engine. Renewable Energy 2003;28:2405–15.
[117] Singh PJ, Khurma J, Singh A. Preparation, characterisation, engine performance and emission characteristics of coconut oil based hybrid fuels. Renewable Energy 2010;35:2065–70.
[118] Canakci M, Monyem A, Gerpen JV. Accelerated oxidation process in biodiesel. Transactions of the American Society of Agricultural Engineers 2005;42:1565–72.
[119] Yahya A, Marley SJ. Physical and chemical characterization of methyl soyoil and methyl tallow esters as CI engine fuels. Biomass and Bioenergy 1994;6:321–8.
[120] Pryor RW, Hanna MA, Schinstock JL, Bashford LL. Soybean oil fuel in a small diesel engine. Transactions of the American Society of Agricultural Engineers 1983;26:333–7.
[121] Candeia RA, Geng LM, Chen H, Bian YZ, Liu J, Ren XC. Influence of soybean biodiesel content on basic properties of biodiesel–diesel blends. Fuel 2009;88:738–43.
[122] Qi DH, et al. Combustion and performance evaluation of a diesel engine fuelled with biodiesel produced from soybean crude oil. Renewable Energy 2009;34:2706–13.

[123] Osborne D, Fritz S, Glenn D. The effects of biodiesel fuel blends on exhaust emissions from a general electric tier 2 line-haul locomotive. Transactions of ASME Journal of Engineering for Gas Turbines and Power 2011;133 102803–1–7.
[124] Kim MY, Yoon SH, Hwang JW, Lee CS. Characteristics of particulate emissions of compression ignition engine fueled with biodiesel derived from soybean. Transactions of ASME Journal of Engineering for Gas Turbines and Power 2008;130 052805-1-7.
[125] Pereira RG, Oliveira CD, Oliveira JL, Oliveira PCP, Fellows CE, Piamba OE. Exhaust emissions and electric energy generation in a stationary engine using blends of diesel and soybean biodiesel. Renewable Energy 2007;32: 2453–60.
[126] Canakci M. Combustion characteristics of a turbocharged DI compression ignition engine fuelled with petroleum diesel fuels and biodiesel. Bioresource Technology 2007;98:1167–75.
[127] Chang DYZ, Gerpen JHV, Lee I, Johnson LA, Hammond EG, Marley SJ. Fuel properties and emissions of soybean oil esters as diesel fuel. Journal of the American Oil Chemists Society 1996;73:1549–55.
[128] Moscherosch BW, Polonowski CJ, Miers SA, Nabe JD. Combustion and emissions characterization of soy methyl ester biodiesel blends in an automotive turbocharged diesel engine. Transactions of ASME Journal of Engineering for Gas Turbines and Power 2010;132(9) 092806-1-11.
[129] Corley RHV. How much palm oil do we need? Environmental Science & Policy 2008;12:134–9.
[130] Bari S, Lim TH, Yu CW. Effect of preheating of crude palm oil (CPO) on injection system, performance and emission of a diesel engine. Renewable Energy 2002;27:339–51.
[131] Yusaf TF, Yousif BF, Elawad MM. Crude palm oil fuel for diesel-engines: experimental and ANN simulation approaches. Energy 2011;36:4871–8.
[132] Kalam MA, Masjuki HH. Emissions and deposit characteristics of a small diesel engine when operated on preheated crude palm oil. Biomass and Bioenergy 2004;27:289–97.
[133] Almeida SCA, Belchior CR, Nascimento MVG, LDSR Vieira, Fleury G. Performance of a diesel generator fuelled with palm oil. Fuel 2002;81:2097–102.
[134] Ng JH, Ng HK, Gan S. Characterisation of engine-out responses from a light-duty diesel engine fuelled with palm methyl ester (PME). Applied Energy 2012;90:58–67.
[135] Kalam MA, Masjuki HH. Biodiesel from palm oil—an analysis of its properties and potential. Biomass and Bioenergy 2002;23:471–9.
[136] Canakci M, Turkcan A, Ozsezen AN. Combustion analysis of preheated crude sunflower oil in an IDI diesel engine. Biomass and Bioenergy 2009;33(5):760–7.
[137] Karaosmanoglu F, Kurt G, Ozaktas T. Long term CI engine test of sunflower oil. Renewable Energy 2000;19:219–21.
[138] Kaufman KR, Ziejewski M. Sunflower methyl esters for direct injected diesel engines. American Society of Agricultural Engineers 1984;27(6):1626–1633.
[139] Rakopoulos CD, Rakopoulos DC, Hountalas DT, Giakoumis EG, Andritsakis EC. Performance and emissions of bus engine using blends of diesel fuel with bio-diesel of sunflower or cottonseed oils derived from Greek feedstock. Fuel 2008;87:147–57.
[140] Hasimoglu C, Ciniviz M, Ozsert I, Icingur Y, Parlak A, Salman MS. Performance characteristics of a low heat rejection diesel engine operating with biodiesel. Renewable Energy 2008;33(7):1709–15.
[141] Lin L, Ying D, Chaitep S, Vittayapadung S. Biodiesel production from crude rice bran oil and properties as fuel. Applied Energy 2009;86:681–8.
[142] Ju Y, Vali SR. Rice bran oil as a potential feedstock for biodiesel: a review. Journal of Scientific and Industrial Research 2005;64:866–82.
[143] Lee CS, Park SW, Kwon S. An experimental study on the atomization and combustion characteristics of biodiesel-blended fuels. Energy and Fuels 2005;19:2201–8.
[144] Agarwal D, Sinha S, Agarwal AK. Experimental investigation of control of NO_x emissions in biodiesel-fueled compression ignition engine. Renewable Energy 2006;31:2356–69.
[145] Agarwal AK, Dhar A. Comparative performance, emission, and combustion characteristics of rice-bran oil and its biodiesel in a transportation diesel engine. Transactions of ASME Journal of Engineering for Gas Turbines and Power 2010;132 064503-1-4.
[146] Sinha S, Agarwal AK. Experimental investigation of the effect of biodiesel utilization on lubricating oil degradation and wear of a transportation CIDI engine. Transactions of ASME Journal of Engineering for Gas Turbines and Power 2010;132 042801-0421.
[147] Hazar H, Aydin H. Performance and emission evaluation of a CI engine fuelled with preheated raw rapeseed oil (RRO)—diesel blends. Applied Energy 2010;87:786–90.
[148] Labeckas G, Slavinskas S. Performance of direct-injection off-road diesel engine on rapeseed oil. Renewable Energy 2006;31:849–63.
[149] Nwafor OMI. Emission characteristics of diesel engine operating on rapeseed methyl ester. Renewable Energy 2004;29:119–29.
[150] Jeong G, Oh YT, Park DH. Emission profile of rapeseed methyl ester and its blend in a diesel engine. Applied Biochemistry and Biotechnology 2006;129: 165–78.
[151] Tsolakis A, Megaritis A, Wyszynski ML, Theinnoi K. Engine performance and emissions of a diesel engine operating on diesel-RME (rapeseed methyl ester) blends with EGR (exhaust gas recirculation). Energy 2007;32:2072–80.
[152] Makareviciene V, Janulis P. Environmental effect of rapeseed oil ethyl ester. Renewable Energy 2003;28:2395–403.
[153] Pugazhvadivu M, Jeyachandran K. Investigations on the performance and exhaust emissions of a diesel engine using preheated waste frying oil as fuel. Renewable Energy 2005;30:2189–202.
[154] Abu-Jrai A, Yamin JA, Al-Muhtaseb AH, Hararah MA. Combustion characteristics and engine emissions of a diesel engine fueled with diesel and treated waste cooking oil blends. Chemical Engineering Journal 2011;172:129–36.
[155] Lin Y, Wu YG, Chang C. Combustion characteristics of waste-oil produced biodiesel/diesel fuel blends. Fuel 2007;86:1772–80.
[156] Ghobadian B, Rahimi H, Nikbakht AM, Najafi G, Yusaf TF. Diesel engine performance and exhaust emission analysis using waste cooking biodiesel fuel with an artificial neural network. Renewable Energy 2009;34:976–82.
[157] Hirkude JB, Padalkar AS. Performance and emission analysis of a compression ignition Engine operated on waste fried oil methyl esters. Applied Energy 2012;90:68–72.
[158] Murillo S, Miguez JL, Porteiro J, Granada E, Moran JC. Performance and exhaust emissions in the use of biodiesel in outboard diesel engines. Fuel 2007;86:1765–71.
[159] Utlu Z, Kocak MS. The effect of biodiesel fuel obtained from waste frying oil on direct injection diesel engine performance and exhaust emissions. Renewable Energy 2008;33:1936–41.
[160] Al-Widyan MI, Tashtoush G, Abu-Qudais M. Utilization of ethyl ester of waste vegetable oils as fuel in diesel engines. Fuel Processing Technology 2002;76:91–103.
[161] Kerihuel A, Kumar MS, Bellettre J, Tazerout M. Ethanol animal fat emulsions as a diesel engine fuel—Part 1: Formulations and influential parameters. Fuel 2006;85:2640–5.
[162] Ralph EHS. Tallow esters as an alternative diesel fuel. Transactions of the American Society of Agricultural Engineers 1985;28(3):716–21.
[163] Oner C, Altun S. Biodiesel production from inedible animal tallow and an experimental investigation of its use as alternative fuel in a direct injection diesel engine. Applied Energy 2009;86:2114–20.
[164] Kumar MS, Kerihuel A, Bellettre J, Tazerout M. Experimental investigations on the use of preheated animal fat as fuel in a compression ignition engine. Renewable Energy 2005;30:1443–56.
[165] Guru M, Koca A, Can O, Cınar C, Sahin F. Biodiesel production from waste chicken fat based sources and evaluation with Mg based additive in a diesel engine. Renewable Energy 2010;35:637–43.
[166] Wu W, et al. Low-temperature property and engine performance evaluation of ethyl and isopropyl esters of tallow and grease. Journal of the American Oil Chemists Society 1998;75(9):1173–8.
[167] Godiganur S, Murthy CS, Reddy RP. Performance and emission characteristics of a Kirloskar HA394 diesel engine operated on fish oil methyl esters. Renewable Energy 2010;35:355–9.
[168] Haldar SK, Ghosh BB, Nag A. Utilization of unattended Putranjiva roxburghii non-edible oil as fuel in diesel engine. Renewable Energy 2009;34:343–7.
[169] Anand BP, Saravanan CG, Srinivasan CA. Performance and exhaust emission of turpentine oil powered direct injection diesel engine. Renewable Energy 2010;35:1179–84.
[170] Li S, et al. Biodiesel production from Eruca Sativa Gars vegetable oil and motor, emissions properties. Renewable Energy 2009;34:1871–6.
[171] Aliyu B, et al. Performance and exhaust emissions of a diesel engine fuelled with *Croton megalocarpus* (musine) methyl ester. Applied Thermal Engineering 2011;31:36–41.
[172] Devan PK, Mahalakshmi NV. Performance, emission and combustion characteristics of poon oil and its diesel blends in a DI diesel engine. Fuel 2009;88(5):861–7.
[173] Mbarawa M. Performance, emission and economic assessment of clove stem oil–diesel blended fuels as alternative fuels for diesel engines. Renewable Energy 2008;33:871–82.
[174] Deshmukh SJ, Bhuyar LB. Transesterified hingan (Balanites) oil as a fuel for compression ignition engines. Biomass and Bioenergy 2009;33:108–12.
[175] Mallikappa DN, Reddy RP, Murthy CSN. Performance and emission characteristics of double cylinder CI engine operated with cardanol biofuel blends. Renewable Energy 2012;38:150–4.
[176] Gumus M, Kasifoglu S. Performance and emission evaluation of a compression ignition engine using a biodiesel (apricot seed kernel oil methyl ester) and its blends with diesel fuel. Biomass and Bioenergy 2010;34:134–9.
[177] Gumus M. A comprehensive experimental investigation of combustion and heat release characteristics of a biodiesel (hazelnut kernel oil methyl ester) fueled direct injection compression ignition engine. Fuel 2010;89:2802–14.
[178] Panwar NL, Shrirame HY, Rathore NS, Jindal S, Kurchania AK. Performance evaluation of a diesel engine fueled with methyl ester of castor seed oil. Applied Thermal Engineering 2010;30:245–9.
[179] Foidl N, Foidl G, Sanchez M, Mittelbach M, Hackel S. *Jatropha curcas* L. as a source for the production of biofuel in Nicaragua. Bioresource Technology 1996;58:77–82.
[180] Conceic-ao MM. Thermoanalytical characterization of castor oil biodiesel. Renewable and Sustainable Energy Reviews 2007;11:964–75.
[181] Canoira L, et al. Fatty acid methyl esters (FAMEs) from castor oil: production process assessment and synergistic effects in its properties. Renewable Energy 2010;35:208–17.
[182] Canakci M, Van Gerpen JH. Biodiesel production from oils and fats with high free fatty acids. Transactions of the American Society of Agricultural Engineers 2001;44(6):1429–36.

[183] Goering CE, Schwab AW, Dangherty MJ, Pryde EH, Heakin AJ. Fuel properties of eleven vegetable oils. Transactions of the American Society of Agricultural Engineers 1982;25(6):1472–7.
[184] Shehata MS, Razek SMA. Experimental investigation of diesel engine performance and emission characteristics using jojoba/diesel blend and sunflower oil. Fuel 2011;90:886–97.
[185] Anand K, Sharma RP, Mehta PS. A comprehensive approach for estimating thermo-physical properties of biodiesel fuels. Applied Thermal Engineering 2011;31:235–42.
[186] Wyatt VT, et al. Fuel properties and nitrogen oxide emission levels of biodiesel produced from animal fats. Journal of the American Oil Chemists Society 2005;82(8):585–91.
[187] Srivastava A, Prasad R. Triglycerides-based diesel fuels. Renewable and Sustainable Energy Reviews 2000;4:111–33.
[188] Schönborn A, et al. The influence of molecular structure of fatty acid monoalkyl esters on diesel combustion. Combustion and Flame 2009;156: 1396–412.
[189] Goodrum JW, Geller DP. Influence of fatty acid methyl esters from hydroxylated vegetable oils on diesel fuel lubricity. Bioresource Technology 2005;96:851–5.
[190] Lin C, Li R. Fuel properties of biodiesel produced from the crude fish oil from the soapstock of marine fish. Fuel Processing Technology 2009;90:130–6.
[191] Puhan S, Saravanan N, Nagarajan G, Vedaraman N. Effect of biodiesel unsaturated fatty acid on combustion characteristics of a DI compression ignition engine. Biomass and Bioenergy 2010;34:1079–88.
[192] Lin B, Huang J, Huang D. Experimental study of the effects of vegetable oil methyl ester on DI diesel engine performance characteristics and pollutant emissions. Fuel 2009;88:1779–85.
[193] Ali Y, Hanna MA. Alternative diesel fuels from vegetable oil. Bioresource Technology 1994;50:153–63.
[194] Serdari A, Fragioudakis K, Kalligerce S. Impact of using biodiesel of different origin and the additives on the performance of stationary diesel engine. Transactions of the American Society of Mechanical Engineers 2000;22:624–31.
[195] Warabi Y, Kusdiana D, Saka S. Biodiesel fuel from vegetable oil by various supercritical alcohols. Applied Biochemistry and Biotechnology 2004;113–116: 793–801.
[196] Agarwal AK. Biofuels (alcohols and biodiesel) applications as fuels for internal combustion engines. Progress in Energy and Combustion Science 2007;33:233–71.
[197] Ong HC, Mahlia TMI, Masjuki HH, Norhasyima RS. Comparison of palm oil, *Jatropha curcas* and *Calophyllum inophyllum* for biodiesel: a review. Renewable and Sustainable Energy Reviews 2011;15:3501–15.
[198] Nakpong P, Wootthikanokkhan S. High free fatty acid coconut oil as a potential feedstock for biodiesel production in Thailand. Renewable Energy 2010;35:1682–7.
[199] Benjumea P, Agudelo J, Agudelo A. Basic properties of palm oil biodiesel–diesel blends. Fuel 2008;87:2069–75.
[200] Tsai WT, Lin CC, Yeh CW. An analysis of biodiesel fuel from waste edible oil in Taiwan. Renewable and Sustainable Energy Reviews 2007;11:838–57.
[201] Kaya C, et al. Methyl ester of peanut (*Arachis hypogea* L.) seed oil as a potential feedstock for biodiesel production. Renewable Energy 2009;34: 1257–60.
[202] Wu F, Wang J, Chen W, Shuai S. A study on emissions performance of a diesel engine fueled with five typical methyl ester biodiesels. Atmospheric Environment 2009;43:1481–5 2009.
[203] Puhan S, Gopinath A, Nagarajan G. Combustion, performance and emission characteristics of a DI CI engine using biodiesel with varied fatty acid composition. International Journal of Renewable Energy Technology 2009;1(1):81–100.
[204] Ng HK, Gan S. Combustion performance and exhaust emissions from the non-pressurised combustion of palm oil biodiesel blends. Applied Thermal Engineering 2010;30(16):2476–84.
[205] Alptekin E, Canakci M. Determination of the density and the viscosities of biodiesel–diesel fuel blends. Renewable Energy 2008;33:2623–30.
[206] Satyanarayana M, Muraleedharan C. A comparative study of vegetable oil methyl esters (biodiesels). Energy 2011;36:2129–37.
[207] Gopinath A, Puhan S, Nagarajan G. Theoretical modeling of iodine value and saponification value of biodiesel fuels from their fatty acid composition. Renewable Energy 2009;34:1806–11.
[208] Knothe G. Structure indices in FA chemistry. How relevant is the iodine value? Journal of the American Oil Chemists Society 2002;79(9):847–54.
[209] Graboski MS, McCormick RL. Combustion of fat and vegetable oil derived fuels in diesel engines. Progress in Energy and Combustion Science 1998;24: 125–64.
[210] Rakopoulos DC. Heat release analysis of combustion in heavy-duty turbocharged diesel engine operating on blends of diesel fuel with cottonseed or sunflower oils and their bio-diesel. Fuel 2012;96:524–34.
[211] Rakopoulos DC, et al. Comparative environmental behavior of bus engine operating on blends of diesel fuel with four straight vegetable oils of Greek origin: sunflower, cottonseed, corn and olive. Fuel 2011;90:3439–46.
[212] Kalligeros S, et al. An investigation of using biodiesel/marine diesel blends on the performance of a stationary diesel engine. Biomass and Bioenergy 2003;24:141–9.
[213] Hoekman SK. Review of biodiesel composition, properties, and specifications. Renewable and Sustainable Energy Reviews 2012;16:143–69.
[214] Ramadas AS, Jayaraj S, Muraleedharan C, Padmakumari K. Artificial neural networks used for the prediction of the cetane number of biodiesel. Renewable Energy 2006;31:2524–33.
[215] Wadumesthrige K. Investigation of the parameters affecting the cetane number of biodiesel. Journal of the American Oil Chemists Society 2008;85:1073–81.
[216] Knothe G, Matheaus AC, Ryan III TW. Cetane numbers of branched and straight-chain fatty esters determined in an ignition quality tester. Fuel 2003;82:971–5.
[217] Canakci M, Gerpen JHV. Biodiesel production from oils and fats with high free fatty acids. Transactions of the American Society of Agricultural Engineers 2001;44(6):1429–36.
[218] Knothe G, Bagby MO, Ryan TW. Precombustion of fatty acids and esters of biodiesel. A possible explanation for differing cetane numbers. Journal of the American Oil Chemists Society 1998;75(8):1007–13.
[219] Erol M, Haykiri-Acma H, Kucukbayrak S. Calorific value estimation of biomass from their proximate analyses data. Renewable Energy 2010;35: 170–3.
[220] Pérez A. Winterization of peanut biodiesel to improve the cold flow properties. Bioresource Technology 2010;101:7375–81.
[221] Lopes JCA, et al. Prediction of cloud points of biodiesel. Energy and Fuels 2008;22:74752.
[222] Lee L, Johnson LA, Hammond EC. Use of branched-chain esters to reduce the crystallization temperature. Journal of the American Oil Chemists Society 1995;72(10):1155–60.
[223] Pratas MJ, et al. Densities and viscosities of fatty acid methyl and ethyl esters. Journal of Chemical and Engineering Data 2010;55(9):3983–90.
[224] Knothe G, Steidley KR. Kinematic viscosity of biodiesel fuel components and related compounds. Influence of compound structure and comparison to petrodiesel fuel components. Fuel 2005;84:1059–65.
[225] Gao Y, et al. Experimental study of the spray characteristics of biodiesel based on inedible oil. Biotechnology Advances 2009;27:616–24.
[226] Dzida M, Prusakiewiez P. The effect of temperature and pressure on the physicochemical properties of petroleum diesel oil and biodiesel fuel. Fuel 2008;87:1941–8.
[227] Lapuerta M, Rodriguez-Fernandez J, Armas O. Correlation for the estimation of the density of fatty acid esters fuels and its implications. A proposed biodiesel cetane index. Chemistry and Physics of Lipids 2010;163:720–7.
[228] Smith PC, Ngothai Y, Nguyen QD, O'Neill BK. Improving the low-temperature properties of biodiesel: methods and consequences. Renewable Energy 2010;35:1145–51.
[229] Knothe G. Biodiesel and renewable diesel: a comparison. Progress in Energy and Combustion Science 2010;36:364–73.
[230] Knothe G. Dependence of biodiesel fuel properties on the structure of fatty acid alkyl esters. Fuel Processing Technology 2005;86:1059–70.
[231] Banapurmath NR, Tewari PG, Hosmath RS. Performance and emission characteristics of a DI compression ignition engine operated on Honge, jatropha and sesame oil methyl esters. Renewable Energy 2008;33:1982–8.
[232] Sarathy SM, et al. A comparison of saturated and unsaturated C4 fatty acid methyl esters in an opposed flow diffusion flame and a jet stirred reactor. Proceedings of the Combustion Institute 2007;31:1015–22.
[233] Nettles-Anderson SL, Olsen DB. Survey of straight vegetable oil composition impact on combustion properties. SAE paper 2009-01-0487; 2009.
[234] Kalam MA, Masjuki HH, Jayed MH, Liaquat AM. Emission and performance characteristics of an indirect ignition diesel engine fuelled with waste cooking oil. Energy 2011;36:397–402.
[235] Lapuerta M, et al. Effect of the alcohol type used in the production of waste cooking oil biodiesel on diesel performance and emissions. Fuel 2008;87: 3161–9.
[236] Lin CY, Lin HA. Diesel engine performance and emission characteristics of biodiesel produced by the peroxidation process. Fuel 2006;85:298–305.
[237] Lin CY, Chiu CC. Burning characteristics of palm-oil biodiesel under long-term storage conditions. Energy Conservation Management 2010;51: 1464–7.
[238] Usta N, et al. Combustion of biodiesel fuel produced from hazelnut soapstock/waste sunflower oil mixture in a diesel engine. Energy Conservation Management 2005;46:741–55.
[239] Song J-T, Zhang C-H. An experimental study on the performance and exhaust emissions of a diesel engine fuelled with soybean oil methyl ester. Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering 2008;222(12):2487–96.
[240] Sahoo PK, Das LM, Babu MKG, Naik SN. Biodiesel development from high acid value polanga seed oil and performance evaluation in a CI engine. Fuel 2007;86:448–54.
[241] Reyes JF, Sepulveda MA. PM-10 emissions and power of a diesel engine fuelled with crude and refined biodiesel from salmon oil. Fuel 2006;85: 1714–9.
[242] Ozgunay HC, Olak S, Zengin G, Sari O, Sarikahya H, Yuceer L. Performance and emission study of biodiesel from leather industry pre-fleshings. Waste Management 2007;27:1897–901.
[243] Ulusoy Y, Tekin YC, Etinkaya M, Kapaosmanoglu F. The engine tests of biodiesel from used frying oil. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects 2004;26:927–32.
[244] Nabi N, Akhter S, Shahadat MZ. Improvement of engine emissions with conventional diesel fuel and diesel–biodiesel blends. Bioresource Technology 2006;97:372–8.

[245] Zheng M, Mulenga MC, Reader GT, Wang M, Ting DSK, Tjong J. Biodiesel engine performance and emissions in low temperature combustion. Fuel 2008;87(6):714–22.
[246] Knothe G, Sharp CA, Ryan TW. Exhaust emissions of biodiesel, petrodiesel, neat methyl ester and alkanes in a new technology engine. Energy and Fuels 2006;20:403–8.
[247] Szybist JP, Boehman AL, Taylor JD, McCormick RL. Evaluation of formation strategies to eliminate the biodiesel NO_x effect. Fuel Processing Technology 2005;85:1109–26.
[248] McCormick RL, Graboski MS, Alleman TL, Herring AM. Impact of biodiesel source material and chemical structure on emissions of criteria pollutants from a heavy-duty engine. Environmental Science and Technology 2001;35(9):1742–7.
[249] Chen H, Shuai S, Wang J. Study on combustion characteristics and PM emission of diesel engines using ester-ethanol-diesel blended fuels. Proceedings of the Combustion Institute 2007;31:2981–9.
[250] Puhan S, et al. Mahua oil (*Madhuca indica* seed oil) methyl ester as biodiesel-preparation and emission characteristics. Biomass and Bioenergy 2005;28(1):87–93.
[251] Lapuerta M, Rodriguez-Fernandez J, Agudelo JR. Diesel particulate emissions from used cooking oil biodiesel. Bioresource Technology 2008;99:731–40.
[252] Tree DR, Svensson KI. Soot processes in compression ignition engines. Progress in Energy and Combustion Science 2007;33:272–309.
[253] Lapuerta M, Armas O, Ballesteros R. Diesel particulate emissions from biofuels derived from Spanish vegetable oils. SAE 2002-01-1657;2002.
[254] Rehman A, Phalke DR, Pandey R. Alternative fuel for gas turbine: esterified jatropha oil–diesel blend. Renewable Energy 2011;36:2635–40.
[255] Shi X, et al. Emission characteristics using methyl soyate-ethanol-diesel fuel blends on a diesel engine. Fuel 2005;84:1543–9.
[256] Labeckas G, Slavinskas S. The effect of rapeseed oil methyl ester on direct injection diesel engine performance and exhaust emissions. Energy Conservation Management 2006;47:1954–67.
[257] Mani M, Subash C, Nagarajan G. Performance, emission and combustion characteristics of a DI diesel engine using waste plastic oil. Applied Thermal Engineering 2009;29:2738–44.
[258] Gumus M. Evaluation of hazelnut kernel oil of Turkish origin as alternative fuel in diesel engines. Renewable Energy 2008;33:2448–57.